AD-A015 057

# SIMULATION OF A WORLD-WIDE SEISMIC SURVEILLANCE NETWORK


Edward M. Shoup, et al

Texas Instruments, Incorporated



Prepared for:

Advanced Research Projects Agency
Air Force Technical Applications Center

31 December 1974

ALEX(01)-TR-74-13

# SIMULATION OF A WORLD-WIDE SEISMIC SURVEILLANCE NETWORK



## TECHNICAL REPORT NO. 13

## VELA NETWORK EVALUATION AND AUTOMATIC PROCESSING RESEARCH

Prepared by
Edward M. Shoup and Robert L. Sax

TEXAS INSTRUMENTS INCORPORATED
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Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Alexandria, Virginia 22314

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Monitoring Research Office
ARPA Program Code No. 4F10
ARPA Order No. 2551



31 December 1974

Acknowledgment: This research was supported by the Advanced Research Projects Agency, Nuclear Monitoring Research Office, under Project VELA-UNIFORM, and accomplished under the technical direction of the Air Force Technical Applications Center under Contract No. F08606-74-C-0033.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

**REPORT DOCUMENTATION PAGE**

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
SIMULATION OF A WORLD-WIDE SEISMIC SURVEILLANCE NETWORK

5. TYPE OF REPORT & PERIOD COVERED
Technical

6. PERFORMING ORG. REPORT NUMBER
ALEX(01)-TR-74-13

7. AUTHOR(s)
Edward M. Shoup and Robert L. Sax

8. CONTRACT OR GRANT NUMBER(s)
F08606-74-C-0033

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Texas Instruments Incorporated
Equipment Group
Dallas, Texas 75222

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
VELA T/4705/B/ETR

11. CONTROLLING OFFICE NAME AND ADDRESS
Advanced Research Projects Agency
Nuclear Monitoring Research Office
Arlington, Virginia 22209

12. REPORT DATE
31 December 1974

13. NUMBER OF PAGES
143

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
Air Force Technical Applications Center
VELA Seismological Center
Alexandria, Virginia 22314

15. SECURITY CLASS (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

ARPA Order No. 2551

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Seismology
Simulation
Surveillance System
Data Communications
Kalman Filter

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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20. continued

obtained on reliability, delays, queues, and capability for two system alternatives and for a range of design parameter settings.

It was concluded that the number of data path failures may present a major problem to the system's management but is not expected to impact the network capability. The major time delay in the network is due to the time to send waveform messages to the central facility so that if subsequently all traces are sent, the delay for an event could be excessive. The major queue in the network is at the remote facility for out-going waveform messages. The simulated four-station network-detection capability, when averaged over all regions, is about 0.3 $m_b$ units worse than the theoretical potential of the network. The major limitation on the network performance is in the detection association processor. This is due to an inherent input false-alarm rate limitation of the processor beyond which its performance deteriorates. In addition to these, the report describes results obtained on major subsystems of the surveillance system.

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## ACKNOWLEDGMENT

The authors thank David G. Black and Richard L. Whitelaw who contributed to the design and programming of the simulator. Also, we thank Mrs. C. B. Saunders who, assisted by Mrs. B. C. Taylor, typed the text and prepared the many illustrations of this report.

## ABSTRACT


This study, conducted by Texas Instruments Incorporated, over the period 1 February 1974 to 31 December 1974, extends earlier studies concerning the design and evaluation of a global seismic surveillance system by providing a closer simulation of the physical network for testing alternatives, developing specifications and assessing capability. The simulator employs finite-difference models of major network elements such as communications and signal processing elements. Simulation results were obtained on reliability, delays, queues, and capability for two system alternatives and for a range of design parameter settings.

It was concluded that the number of data path failures may present a major problem to the system's management but is not expected to impact the network capability. The major time delay in the network is due to the time to send waveform messages to the central facility so that if subsequently all traces are sent, the delay for an event could be excessive. The major queue in the network is at the remote facility for out-going waveform messages. The simulated four-station network detection capability, when averaged over all regions, is about 0.3 $m_b$ units worse than the theoretical potential of the network. The major limitation on the network performance is in the detection association processor. This is due to an inherent input false-alarm rate limitation of the processor beyond which its performance deteriorates. In addition to these, the report describes results obtained on major subsystems of the surveillance system.

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# SECTION I

# INTRODUCTION

This simulation study is an extension of earlier work in the design and evaluation of a seismic event monitoring network. A computer program developed by Wirth (1970) estimated the operating characteristics of a network but neglected constraints imposed by response time and the physical system. That program, made more efficient by Wirth in 1971, was applied by Wirth, Blandford, and Shumway (1971) to evaluate an automatic network-level detector. Since then, a study by Sax et al, (1974) identified the major functions and the configuration for a cost-effective network. The current study combines and extends these earlier works by providing the means for evaluating alternative processes at the subsystem and total system levels. It weakens the assumption regarding the physical system and permits evaluation of dynamic behavior, given a procedural or functional alternative.

This report records for later reference the methods for seismic network simulation and describes specific results obtained to date.

The report consists of six sections. Section II defines the problem to be addressed by the simulator designer. In the third section simulator methodology is described. Study results are presented and analyzed in the fourth section. In Section V we draw conclusions and make recommendations regarding the seismic network and its simulation. References are given in Section VI. Formal documentation of the computer programs is not included in this report, but Appendix A describes the general flow of the simulator.

## SECTION II

## STUDY DEFINITION

In this section a description is given of the physical network, the objectives of simulation, subsystem alternatives, design parameters, and analysis elements. These topics provide a problem statement for reference in designing the simulator and serve to indicate the motivation for simulating the network. In short, simulation is regarded as a useful tool for system design and performance evaluation provided the system is large, i.e., many states, and that the system elements interact significantly. If these conditions apply, then selecting element designs by a subsystem criterion does not assure optimality of the total system.

The organization and approach to simulation is critical if it is to be useful. So, before introducing the simulation methodology, we need to consider and keep in mind the problem statement presented in this section.

### A. NETWORK OVERVIEW

Following Sax et al, (1974), the network is organized into three types of facilities: the remote facilities, the communications facilities, and the central facility. The remote facilities include all hardware and software items in the field not involved directly with international communications or communications with the central facility. In most cases, the remote facilities are at overseas locations. The central facility includes all hardware and software items at the hub of the communications network. It is taken to be at a single location in the continental United States. The communications facilities are distributed among the remote facilities and the central facility. This includes all hardware and software items and leased transmission lines necessary for connecting the stations, in a star-like configuration, to the central facility.

1. Remote Facility

This group senses, stores, and processes seismic data in the field. As shown in Figure II-1, a typical remote facility contains three subsystems; the remote sensor units (RSU), the data collection processor (DCP), and the station detection processor (SDP). The RSU consists of eight modules for sensing, converting and transmitting the ground motion data to the DCP. The DCP is comprised of nine elements for storing and performing off-line processing of this data. The SDP performs detection processing and forwards the results to the DCP. Eight elements are identified with the SDP.

2. Communications Facility

This facility has the three subsystems; the remote communications processor (RCP), the international communications channel (ICC), and the central communications processor (CCP). Referring to Figure II-1 again, the RCP is located at the bottom left-hand side. Its function is to read messages from the DCP storage, format them and perform the protocol necessary to transmit the messages. Also, it receives incoming messages and writes them to a designated area of the DCP storage. The ICC is a leased line from each station having a capacity in the range of 50 bits per second (bps) to 4.8 kilobits per second (kbps), depending on the station. The CCP is shown at the top of Figure II-2. It is the primary processor of the communications facility and has the function of reading the disk for outgoing messages, formatting these and performing the protocol necessary for transmission to the remote facility. Also, it receives transmissions from all remote facilities, unpacks and assembles the messages and writes them to the central facility disk.

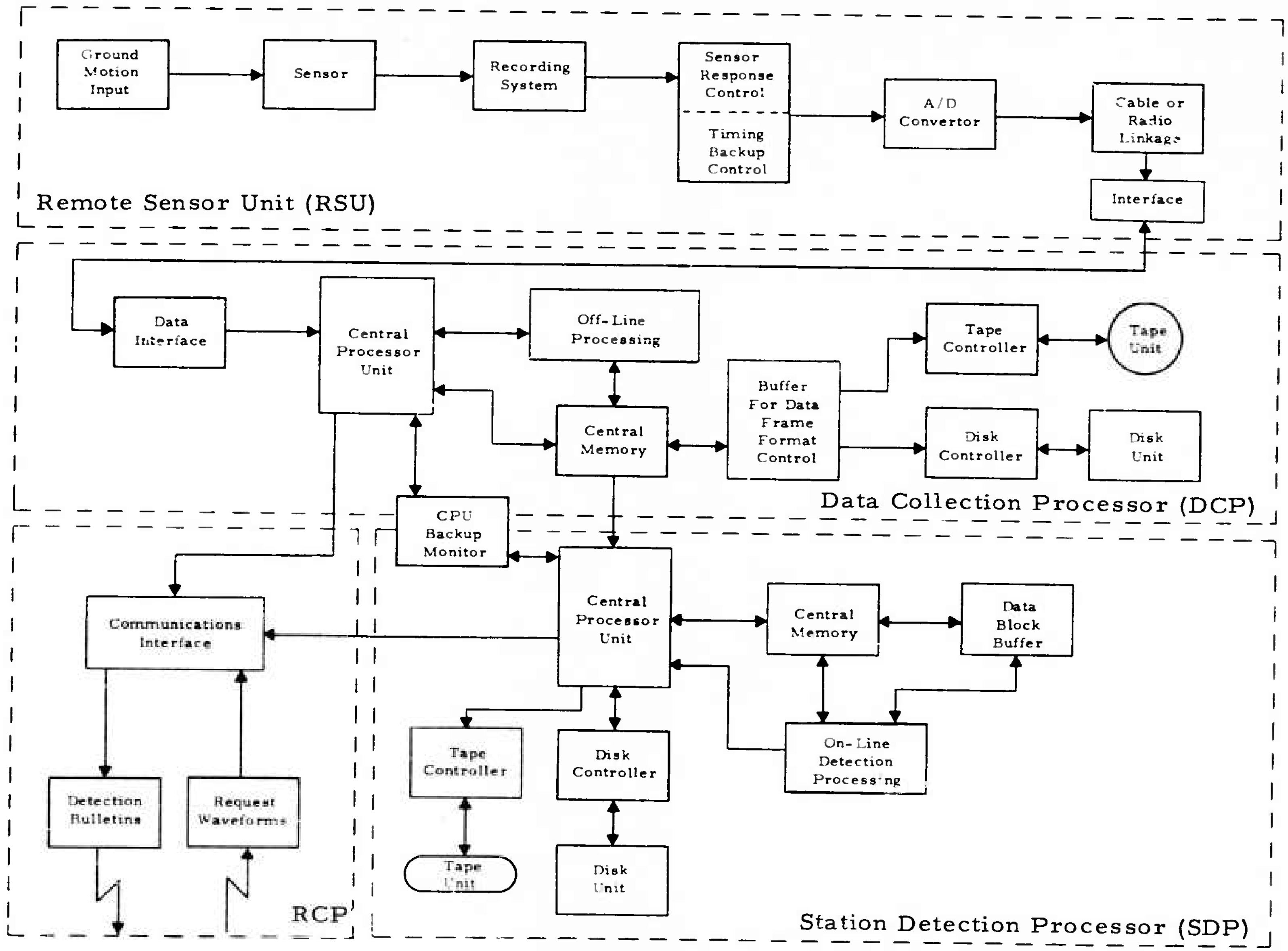



FIGURE II-1

GENERAL CONFIGURATION OF THE REMOTE FACILITY

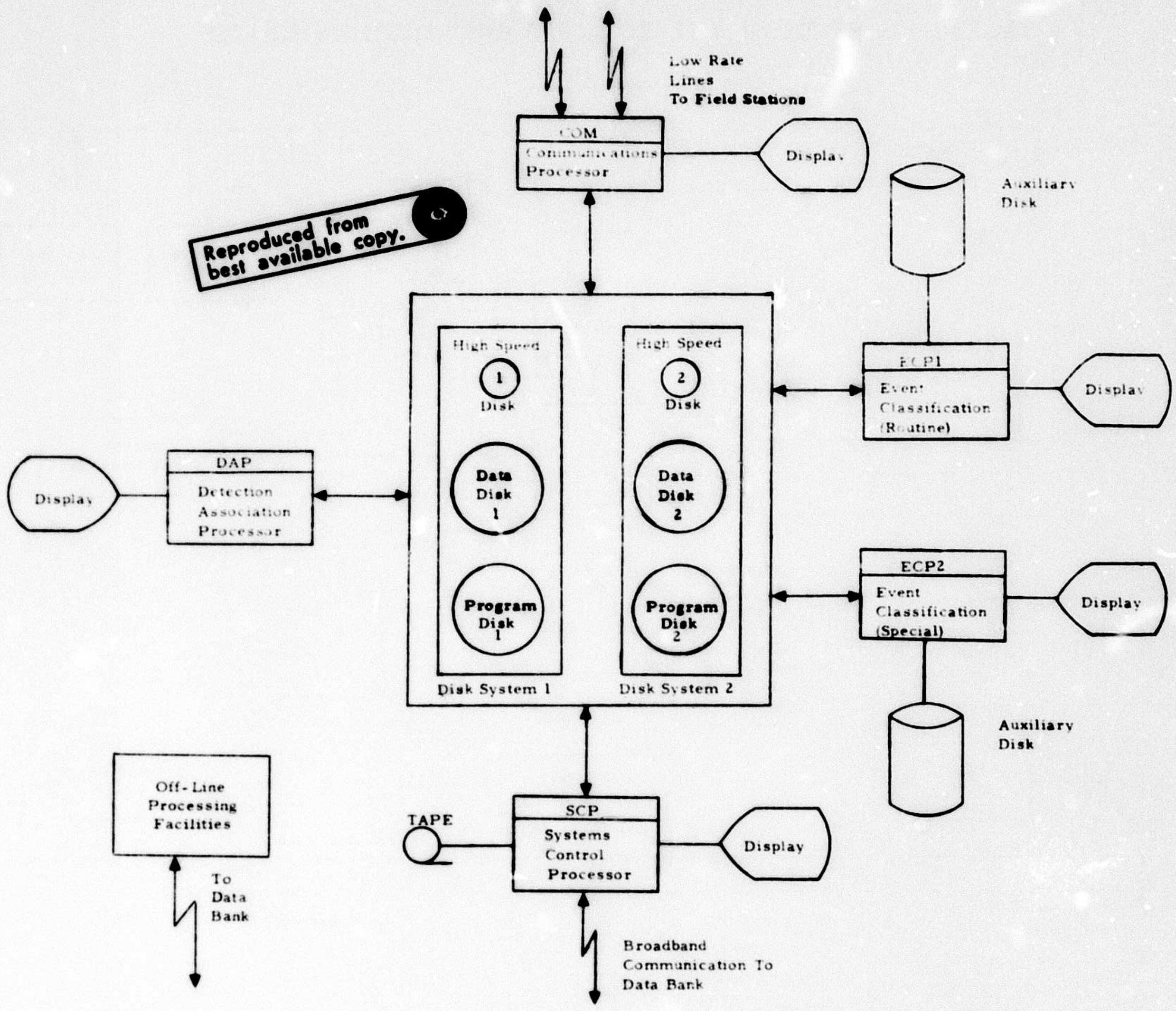



**FIGURE II-2**

**GENERAL CONFIGURATION OF THE CENTRAL FACILITY**

3. Central Facility

As illustrated in Figure II-2, there are four subsystems in the central facility. Their major function is to locate and classify events based on the available information and to store the information for future reference. The subsystems are the detection association processor (DAP), the event classification processor (ECP), the disk storage units, and the system control processor (SCP). The DAP's purpose is to take incoming detection bulletins and to determine by association whether additional data is justified. If so, it issues a data request to the remote facilities containing approximate location and time estimates. The ECP uses all of the resuling measurement data and processed data and makes the final determination as to the class, location, time, and other descriptors of an event. The SCP monitors and aids in controlling the entire network status.

## B. OBJECTIVES

A good simulator will be useful throughout the life-cycle of the seismic surveillance network. During the development phase it is a design aid for evaluating alternatives, for arriving at specifications and for predicting the capability of the network. During the operations phase the simulator can be used for training, for testing policies and procedures, for identifying and justifying needed research, for evaluating research results, and as a management aid in adapting to changing capability or cost requirements.

In evaluation of design alternatives, the simulator provides a test environment for major elements. The test data for station detection processing are provided either by measurement data or an earth model. But for the other elements such as communications processors, the test data are supplied by the surrounding elements. Also, element optimization is promoted by the simulator, for it can be used to evalu   the elements impact on other elements as well as the total system. A third area of benefit is in evaluating operating procedures, e.g., procedures for requesting event waveform data.

For developing specifications of system elements, the simulator can promote smooth integration, reliable operation, and flexibility. This will include identification of all elements necessary for interfacing, storage and standby functions. Bounds or requirements may be developed for memory size, reliability, maintainability, and software execution time.

Increasingly realistic assessments of system capability will result from using the simulator. Easily obtained are dynamic assessments of detection probability, false alarm probability, location error and false association probability. The stability of these measures can be determined under unusual conditions such as event swarms, communications burst errors, or equipment failures. New information can become available on discriminating and resolving space-time clusters of events.

As stated above, the simulator can be applied toward satisfying objectives of the system's operations phase. More specifically, it can contribute to analyst training, operations management, policy and procedure development, and also function as a management information system.

Training applications of the simulator may include operator training. Maintenance personnel may be given diagnostic or trouble-shooting exercises. System operations manager training may also be facilitiated by the simulator.

When abnormal conditions arise the operations manager may inquire about alternate procedures and about the time needed to recover from the failure state. Supplementing this with other data, the manager can make exceptionally well-informed decisions.

Management 'games' can be staged using the simulator. From these the system management can develop policies and procedures or a plan for responding to various 'what if' scenarios such as changing requirements or budgets and for identifying research needs.

Lastly, the simulator can contribute rather directly to a computerized management information system by using sparse status data to train the simulator and then having the simulator reconstruct and report on any state or area of the system in exactly the required detail. From the foregoing, the key application objectives of the simulator may be summarized as:

- Evaluation of design alternatives
  - Test environment
  - Element optimization
  - Procedures optimization.
- Develop specifications
  - Identify necessary elements
  - Develop element parameter values.
- Determine capability
  - Detection and estimation process statistics
  - Stability under peak loads
  - Cluster discrimination process statistics.
- Training aid
  - Operator training
  - Maintenance training
  - Management training.

- Policy development
  - Management games
  - Requirements changes
  - Budget changes.
- Management information system
  - Reconstruct states
  - Report at any level of detail
  - A minimum of data collection.

## C. GUIDELINES

The following guidelines were observed while developing the simulator and performing the simulations.

### 1. Configuration

The simulator models the decentralized system illustrated in Figures II-1 and II-2. This implies that a substantial amount of data processing is done in the field and that low-rate communications (50 bps to 4.8 kbps) are available for transmissions between the field stations and the central facility. The alternative, to use high-rate communications with little data reduction in the field, is not considered cost-effective. This was the conclusion by Sax et al, (1974).

### 2. Network Alternatives

The two decentralized network alternatives (A and B) as developed in the above study are to be compared using the simulator. Briefly, network A is similar to the existing network of several large arrays and 20 single sensor stations; and network B consists of 25 small arrays.

### 3. Level of Detail

The level of the simulation models (micro or macro), is to depend on the significance of the element, the element's newness and the availability of macro-level statistics. Major new elements are usually treated in detail. Major but well-known elements such as sensor units and sensor-to-station communications, where statistics are known, are treated at a macro-level.

### 4. Completeness

Due to time limitations and lack of definition, certain elements are not included in the simulation. In this group are the central facility event classification processor and system control processor.

### 5. Analysis

In addition to representing candidate elements, the simulator is to provide loading data on the communications and seismic processors and to be capable of simulating alternative operating procedures.

## D. ALTERNATIVES

Within the decentralized network configuration, several subsystem candidates are possible. These lead to alternative systems with significantly different cost-effectiveness attributes. In particular, the SDP at the remote facility, the DAP at the central facility, and their communications linkage appear to be important subsystems with many alternative ways to invest time and money. Table II-1 lists, without definition, approaches which could be studied by simulation. Included are hardware, software, and procedural approaches. Groups of these define a subsystem alternative which

TABLE II-1

SUBSYSTEM APPROACHES
(PAGE 1 OF 2)

| REMOTE FACILITY |
| --- |
| Station Detection Processor |
| * Constant False Alarm Rate |
| Variable False Alarm Rate |
| Frequency Dependent Detection |
| * Broad-Band Detection |
| * Beam Power Detection |
| Beam Power and F-Statistic Detection |
| Fixed Mean Noise Detection |
| Central Facility Control of Threshold |
| * SP Detection |
| SP and LP Detection |
| Later Phase Identification |
| * Single Array Detection |
| Subarray Detection |
| Coda Model Detection |
| Data Collection Processor |
| Variations in the Content of Detection Bulletins |
| Variations in the Response to Waveform Requests |
| * Send Beam Data |
| Send Magnitude Data |
| Send Envelope Data |
| Adaptive Responses Dependent of Data and Workload |

* = Base-line models

TABLE II-1

SUBSYSTEM APPROACHES
(PAGE 2 OF 2)

| COMMUNICATIONS NETWORK |
|---|
| * Stop and Wait Automatic Request Repeat (ARQ) Error Control |
| Continuous ARQ |
| Synchroneous Transmission (little protocol) |
| * Asynchroneous Transmission (protocol) |
| Adaptive Block Size Depending on Error Rates |
| Dynamic Buffering Depending on Demand |
| * Advanced Data Communications Control Procedure |
| Full Duplex Lines |
| * Half Duplex Lines |
| * Teletype Rate Channels |
| Higher Rate Channels |

| CENTRAL FACILITY |
|---|
| Triangulation DAP |
| * Key and Error Ellipse DAP |
| Optimal Search DAP |
| * Array Oriented DAP |
| Single Sensor and Array Oriented DAP |
| Single Sensor Oriented DAP |

* = Base-line models

must be matched with other subsystems to form a system alternative. We see that the SDP approaches range from simple power detectors to a yet to be defined optimal detector. For the simpler approaches, good communications and central facility processing may be necessary for an acceptable system.

Complexity of the initial simulator was not sought. Therefore, the base-line design being simulated is a simple and probably not an optimal design. It is assumed that through simulation a gradually improved design will evolve in stages. Base-line alternatives along with other possibilities are indicated in Table II-1. Base-line models are indicated by asterisks.

## E. DESIGN PARAMETERS

For any given subsystem design there are a number of design parameters. In several cases they represent different specifications for the design. In others, they represent unknown factors such as reliability, the effect of which can be evaluated by the simulator. Table II-2 lists the parameters available in the simulator or those which can easily be entered into the simulation.

In the simulation trials the parameters are to be varied only in cases where they impact the system performance measures. It is not practical to study the effect of every parameter for every element of a given design. Therefore, typical parameter values will be used except for those sensitive parameters.

## F. ELEMENTS OF ANALYSIS

The following list itemizes some elements of analysis that need to be considered in designing the simulator and while analyzing its results.

TABLE II-2

DESIGN PARAMETERS BY FACILITY AND ELEMENT
(PAGE 1 OF 3)

| REMOTE FACILITY |
|---|
| Station Detection Processor |
| MTBF (mean time between failure) |
| MTTR (mean time to repair) |
| Time Gate |
| Threshold |
| Azimuth Error |
| Ray Error |
| Time Error |
| Magnitude, Period |
| Noise Statistics |
| Data Collection Processor |
| MTBF |
| MTTR |
| Delay |
| Remote Storage Element |
| MTBF |
| MTTR |
| Detection Bulletin File (DB) |
| Waveform File (WF) |
| Waveform Request File (WFR) |

TABLE II-2

DESIGN PARAMETERS BY FACILITY AND ELEMENT
(PAGE 2 OF 3)

| COMMUNICATIONS NETWORK |
|---|
| Remote Communications Processor |
| MTBF |
| MTTR |
| DB Buffer |
| WF Buffer |
| WFR Buffer |
| DB Length |
| WF Length |
| WFR Length |
| Block Size |
| International Communications Channel |
| MTBF |
| MTTR |
| Bit Error Probability |
| Data Rate |
| Central Communications Processor |
| MTBF |
| MTTR |
| DB Buffer |
| WF Buffer |
| WFR Buffer |
| DB Length |
| WF Length |
| WFR Length |
| Response Time Limit |
| Block Size |

TABLE II-2

DESIGN PARAMETERS BY FACILITY AND ELEMENT
(PAGE 3 OF 3)

| CENTRAL FACILITY |
|---|
| Detection Association Processor |
| MTBF |
| MTTR |
| Input Work Area |
| Output Area |
| DB Length |
| Number of Detections for an Event |
| Key Selection Parameter |
| Number of Keying Levels |
| Association Confidence Limits |
| Time Limit for New Information |
| Number of Bulletins Before Association Trial |

1. Utilization

This measure may be taken on any subsystem. It gives an indication of the workload balance among processors, availability of equipment for additional processing or the need for backup equipment and procedures. In communications the maximum observed utilization is the efficiency of the communications procedure and can be compared with theoretical values.

2. Reliability

We can determine the element reliability necessary to maintain overall system reliability and capability requirements. Poor reliability impacts operating costs and the system capability. The resultant effect of seemingly reliable components in a proposed configuration is a matter of interest that can be determined by this measure.

3. Queues

Measurement of the queue lengths at the processors and storage elements are used to determine the buffer and storage space requirements, the need for additional capacity or the need for improved procedures.

4. Delays

Processor delays should be such that the overall delay for an event meets requirements. The measure is useful also in developing macromodels of processors.

5. Sensitivity

Those performance measures found to be most sensitive to design parameter variations should be expressed with confidence limits rather than as point values.

6. Stability

Dynamic behavior of the surveillance system can be analyzed by simulation. Other things being equal, we prefer to develop a system which recovered quickly from a failure. Also, systematic variations in capability should be avoided. Considerable amount of simulation and parameter perturbation may be required to achieve stability of the whole system.

7. Observability and Controllability

The observability and controllability of the system reflect which states can be seen and influenced by system operators at all levels. These attributes are inherent in some designs while others would require special procedures.

8. Capability

The overall system effectiveness, which depends on all of the above measures, concerns event detection and estimation errors. Alternatives should be judged by significant differences in relative effectiveness. After the alternatives are well defined and optimized, the simulator should provide reasonable estimates of the capability of a proposed system.

9. Cost and Personnel

In addition to the effectiveness measures, cost and personnel implications of alternatives should be discussed to complete the analysis.

The analysis elements and their principle areas of application are summarized in Table II-3.

TABLE II-3

SUMMARY OF ANALYSIS ELEMENTS

| Element | Principal Area |
|---|---|
| Utilization | Communications and major processors |
| Reliability | As seen from the central facility and for the total system |
| Queue | Requirements for all buffers and files |
| Delay | Determine the age of work and service times for major processors |
| Sensitivity | Study variations of above measures due to parameter uncertainty |
| Stability | Study bounds on time behavior of the above measures |
| Observability and Controllability | Can key states be seen from the central facility? Can faults be corrected or managed? |
| Capability | For seismic processors and the total system |
| Cost and Personnel | Comment on significant cost differences between alternatives. Comment on the personnel implications of alternatives and parameters such as MTTR. |

# SECTION III
# METHODOLOGY

The methodology chosen meets the application objectives identified in the last section. It should be apparent that such diverse objectives are not easily met and certainly not without considerable forethought. Two basic policies were adopted and followed in this methodology. These were: to decompose the system for modeling purposes according to the decomposition of the physical network into subsystems, and secondly, to model the subsystems with finite difference equations.

The first policy states that whenever possible the system is modeled by processors or subsystems and that these are cascaded together to form a facility or a desired total system simulator. The advantage is that the various models correspond to separate research areas, procurement packages, areas of management responsibility and often to separate disciplines. Also, with this approach actual software or hardware can be tested in place of simulated models to gauge their stability and effectiveness in a total system environment. Also, real earth data can be used in such tests rather than the simulated earth model. Other decomposition than cascade may decrease the computer run time slightly but they lose significance to the user when it comes to designing a physical system.

The second policy is that finite difference state models be applied whenever possible. The general form is:

$$X_{k+1} = F_k(X_k, U_k, Y_k, W_k)$$

where,

$k$ = discrete time

$X_k$ = the element state vector

$U_k$ = the element input vector

$Y_k$ = the element parameter vector

$W_k$ = random processes associated with the element.

The advantages of this approach are that it is compact and minimizes computer memory requirements. Also, modeling can be done at both macro and micro-levels. It provides to each element realistic time series which can be assumed in developing models and for establishing a test environment for models or actual modules. Finally, it is most useful for analysis work, optimization, and later for system control functions.

The disadvantage of a micro-model is that it may be operating at a time scale unsuitable for developing long-term statistics. For example, the communications model is in steps of 0.15 seconds for the study of protocol effects. However, to study months of operation of the total system, a macro-model is needed. Two approaches are used to develop the macro-model. The first is to solve the difference equations for larger time steps and the second is modify it using parametric statistics from the micro-model.

Models described as state models, follow three conventions. First, the state vector is usually partitioned into fixed lengths for feedforward (remote facility to central facility) directed states (X(1) to X(10)), feedback (central facility to remote facility) directed states (X(11) to X(20)), and internal states (X(21) to X(n)). Second, to make this section useful to programming, the program indices are shown, which due to changes are not consecutive. Third, input vectors to an element are also partitioned into feedforward (U(1) to U(10)) and feedback (U(11) to U(20)) states.

To the casual reader, the model descriptions serve to illustrate the method and the number of considerations involved. To the reader desiring to develop new models, they provide a starting point. They also aid in communicating the desired procedure to a programmer. Note that although the programmer need not implement the state models directly, the procedure should be the same, delays, temporary storage, round-about flow and so on.

## A. SIMULATOR OVERVIEW

The simulator modules are shown in Figure III-1. The modules represent the subsystems of the network configuration diagrams (Figures II-1 and II-2). For convenience, the modules are designated by subsystem abbreviations.

The flow of information starts with the earth model (EM) at the left of this figure. The earth model generates synthetic but realistic detection data inputs to the network simulator. These enter the remote facility simulator which represents the network from the sensors to the communications facility. Detection bulletins (DB's) generated in the remote facility simulator are forwarded to the communications facility simulator. After protocol and delay steps are performed, the DB's enter the central facility simulator. At the central facility the detection association processor (DAP) simulator reads the available DB's and for each network detection, waveform requests (WFR's) are sent to selected stations. Then, the WFR's are written to the central storage element (CSE), read by the central communications processor (CCP), and sent to the correct remote communications processor (RCP). Last, the remote facility simulator converts WFR's to waveform messages (WF) and sends these back to the central facility for event classification processor (ECP) processing, where the simulation ends for that event.

It is not practical, except for validation or maintenance purposes, to print and evaluate all of the information developed by the simulator.

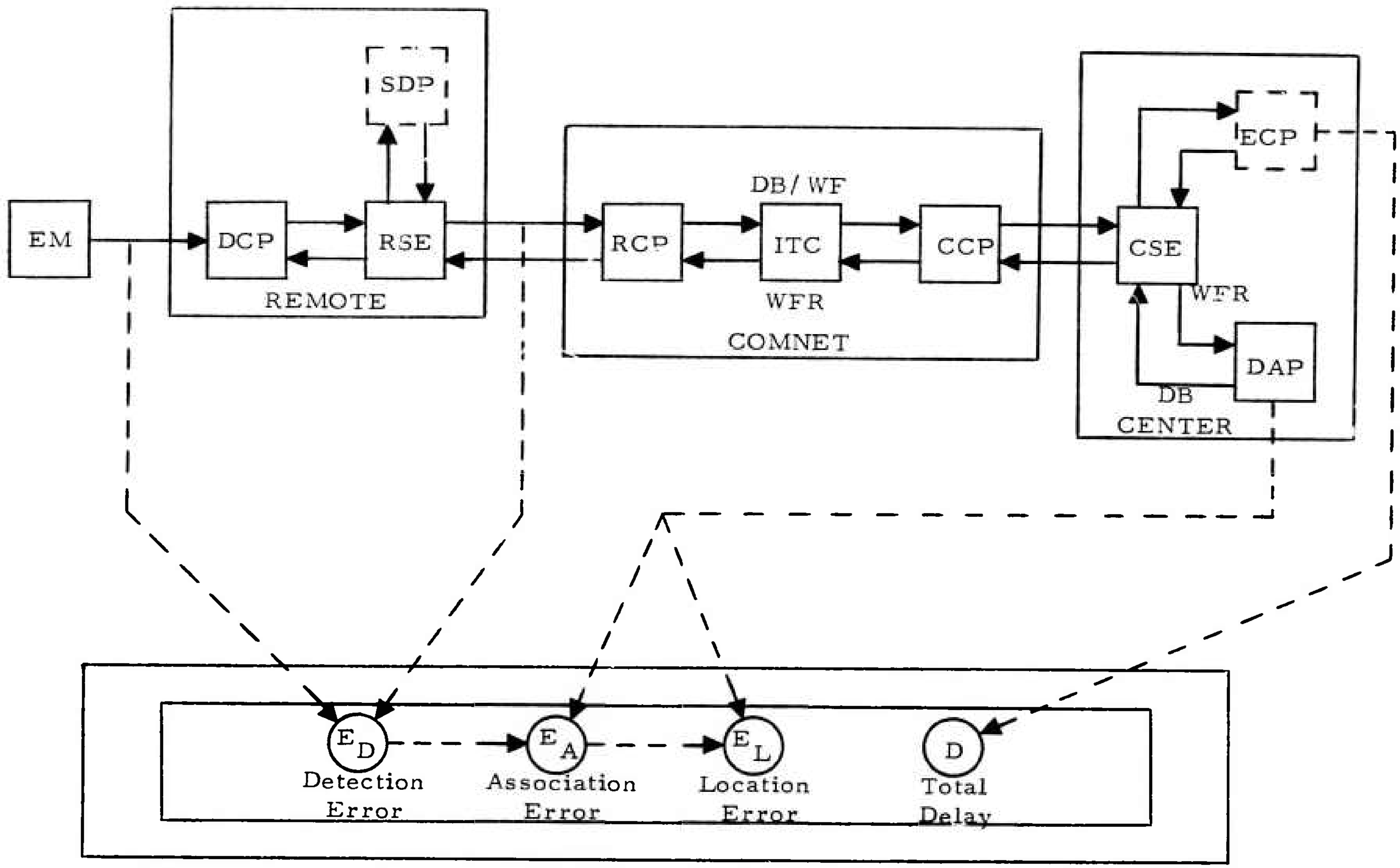



FIGURE III-1

BLOCK DIAGRAM GIVING AN OVERVIEW OF THE SIMULATOR

Therefore, Figure III-1 shows an instrument panel to signify, as with the actual network, the necessity of evaluating by a few well chosen measurements. For this, data are collected and summarized on the network analysis elements. At the total system level, these concern; station detection errors, network detection or association errors, network location and time estimate errors, and the total processing delay for events.

## B. EARTH MODEL

The earth model drives the simulator by generating detection bulletins from each of the individual stations in the network. Events from seismic regions are distributed similarly to those on the earth and will include localized regions of swarm activity. Region seismicity is controlled by the user to attain realistic earth seismicity. Complexities produced by later phases and the coda of earthquakes strongly affect the performance of the system. Random codas are automatically generated with each earthquake as are the most frequently occurring later phases.

For each phase mean transmission parameters are generated. For each focus to station path, parameters such as magnitude and travel time are randomized with zero mean normal statistics. These are path and seismic phase dependent. Path and seismic phase dependent bias in transmission parameters are assumed to be calibrated for each nominal region-station path. The dynamics of generating correction tables are not included in the present scope of the earth model. The earthquake simulation is based on a steady state model which adequately accounts for the fixed bias in transmission characteristics.

Each station SP and LP array dimensions are controlled by the user. The user can also specify the ambient noise level, instrument response, and beam loss characteristics of the station. Transmission measurement errors, dependent on array dimension, S/N ratio, period, and other parameters are adequately accounted for within the earth model.

Although the earth inputs to each station were attempted to be modeled realistically, these are necessarily certain limitations on the simulation. These tradeoffs were made for more efficient computation.

The following are some of the limitations:

- No more than six events can be observed simultaneously.
- In a single time gate at a given station the detector can distinguish no more than two interfering events. Other events occurring cannot be detected. Those that can be detected are:
  - the event with the largest amplitude
  - the first arriving event greater than twice the mean noise.
- No more than 12 events per hour can be unambiguously resolved without risk of losing events due to a limited stack length of 6 events.
- No more than three swarms can be activated at one time.
- Events are uniformly distributed within regions.
- Regional transmission biases are assumed to have been correctly accounted for.
- No more than four event phases were observed at each station.

1. Region Characterization and Source Generation

The seismically active areas of the earth are modeled by defining the boundaries of 100 different source regions. These regions have a uniform probability of being selected to 'produce' an event. Provision is made to shape each region to follow the trend of observed seismicity in the region block. The parameters used to locate and shape each region are as follows:

- Centroid latitude and longitude
- Maximum block latitude and longitude deviation
- Rotation of the rectangular region block
- Curvature of the oriented rectangular region block.

Starting with a rectangular block oriented along a latitude line, the block is transformed into a parabola shaped arc in local geographical coordinates, which is rotated to follow the observed trend of earthquakes. In this way it was possible to accurately represent seismic zones with ninety of these shaped regions. The remaining ten regions were used to represent small localized swarm centers.

Some regions are more populated by events than others. Each region is therefore represented by a relative event population weight between zero and one. When region block is selected, a uniform random number between zero and one is drawn. If the number exceeds the region weight, the seismic zone is not activated.

After selecting a region, uniform random numbers are drawn to generate a location within the region. Further, the depth of focus is determined by generating a log-normal statistic to modify a regional mean depth given that depth variation is modeled statistically by a specified log-standard deviation. The generation of origin time is controlled by a universal seismicity curve with a minimum event magnitude specified by the user. The average number of events per day is log-normally modulated and smoothed with the logarithmic standard deviation and smoothing time constant specified by the user. Using the log-normal realization of average number of events per day, the time interval to the next event is generated as the variate of an exponential distribution. The magnitude probability density is an exponential function at magnitudes greater than the specified minimum magnitude and zero at lesser values.

The corner period or dominant period (for A/T) for each event is generated given the magnitude of the event using a standard corner period versus $M_L$ and $M_L$ versus $m_b$ relationships. Complexity of the event is represented by the time delay between the first motion and the maximum peak amplitude of the event. This time delay is generated by a uniform statistic between zero and one which is squared and multiplied by the maximum delay of 16 seconds. This derived statistic approximately evenly splits the events between simple and complex representations, on the basis of time delays of 4 seconds to the maximum peak.

Swarms are activated by selecting a source region in a partitioned swarm region block. Initially no swarm regions are active. To generate the number in a swarm, a uniform variate between zero and one is multiplied times the maximum number of possible swarm events -- a parameter loaded for each swarm region by the user. Up to three swarm regions can be simultaneously activated, each of which is characterized by a counter specifying the number of remaining earthquakes in the swarm. The probability is close to one for a large number of remaining swarms and drops to about one tenth when the swarm stack is nearly worked off. After a sufficient number of events are generated by one of the active swarms, the counter reaches zero and the region is deactivated and the swarm stack is manipulated to reflect the deletion of an active swarm region.

Source parameters are printed as each source is generated in page blocks of 50 events. The printouts are continuously rolled over to provide book page logs of all events generated. Only the current block of 50 events is held in memory as input to the system simulator. As a new block of 50 events are generated by the simulator, the previous block of event data is printed.

2. Transmission Parameter Generation

The transmission parameters were derived for the earth model for the following phases:

- P $(0^{o} \leq \Delta \leq 104^{o})$
- PKP $(142^{o} \leq \Delta \leq 180^{o})$
- pP $(0^{o} \leq \Delta \leq 104^{o})$
- pPKP $(0^{o} \leq \Delta \leq 180^{o})$
- PcP $(0^{o} \leq \Delta \leq 104^{o})$
- PKIKP $(110^{o} \leq \Delta \leq 180^{o})$
- PP $(0^{o} \leq \Delta \leq 180^{o})$ .

The following mean transmission factors were generated for each source-station-phase path:

- $T(\Delta, Z)$ travel time
- $\frac{\partial T(\Delta, Z)}{\partial \Delta}$ ray parameter
- $B(\Delta, Z)$ B-factor.

The mean B-factor transmission for P waves was modeled by fitting analytical functions to tables given by Veith and Clawson, 1972. Jeffery-Bullen travel time tables were used as a basis for deriving an analytical approximation to the travel times and $dT/d\Delta$. Direction and great circle distance calculations were based on spherical trigonometry. Travel times of the later phases were modeled by fitting analytical functions to travel time tables given by Richter (1958). The B-factors of later phases were scaled to that of P-waves using spherical spreading approximations given by Bullen (1953). These were corrected for absorption by empirically filtering the analytical B-factor approximations to observations of Lambert et al., (1970) with a constant correction. The variance of Lambert's observed magnitudes from those of the calculated B-factors indicated a small standard deviation on the order of 0.15 to 0.2 magnitude units compared to the 0.3 and 0.5 observed between stations.

Therefore the statistical deviation of magnitudes between stations was generated with a zero mean normal distribution of 0.45 magnitude units with an additive deviation of later phases applied to the P-phase station magnitude using a 0.15 standard deviation population. Considerably more investigation of random B-factor deviations would be desirable to improve these models.

Mean coda decay characteristics were modeled. The model was based on observing increases in spectral energy of earthquakes with progressively larger time windows. The observations indicated that energy increased as $T^a$ $(a \leq 1)$. A nominal value obtained for most teleseismic earthquakes was $a = 1/3$. This results in a power measure which is nominally independent of the time window dimension. These observations were the basis for the analytical coda decay model used by the simulator. Random deviations about the apparent mean coda decay were generated using a zero-mean normal statistic with log-standard deviation of 0.15, independently sampled on a time scale larger than the signal pulse width characterized as the dominant period of the signal.

In order that the source and transmission characteristics derived for station observations of simulated events be reproducible independently of the design of the station detector, they were stacked for up to six simultaneously observed events and for all stations. Thus, when changing the time gate and threshold, the false alarm sequence changed but the event dependent observations remained invariant.

### 3. Station Parameter Generation

Each station is described by the user through input parameters by the geographical location, short-period array characteristics, long-period array characteristics, and a signal beam loss parameter. The short-period and long-period array characteristics are as follows:

- Number of sensors
- Average sensor spacing given independent noise at each sensor
- Average single sensor noise mean and standard deviation.

Transmission errors represent distortions generated along the path from the station to the receiver. These errors seen in waves incident to each station were generated as follows:

- Arrival time errors
- Event magnitude errors
- Dominant period errors.

Incident waves are further distorted by station measurement errors which result from using seismic arrays of band limited instruments to sense the incident signal. These errors are as follows:

- Ray parameter ($dT/d\Delta$) errors
- Ray direction errors
- Magnitude errors
- Dominant period errors.

The most precise measurement obtainable at the seismic station is the arrival time. For this errors are generated by a normal distribution with a standard deviation of one second. The transmission error in incident magnitude is generated by a normal distribution with standard deviation of 0.45 as described in the preceding section. The station measurement of magnitude is further distorted by the short-period system response which taken as flat for A/T with 12 dB/octave roll-off points at periods greater than 1.5 seconds and less than 0.55 seconds. The dominant pulse period error due to transmission is generated by a log-normal factor of mean value one and log-standard deviation 0.2. This also is further distorted in measurement by the short-period system response which sees source corner periods greater than 1.5 seconds as apparent corner periods with maximum amplitude at 1.5 seconds; and source corner periods less than 0.55 seconds as apparent corner periods with maximum amplitudes at 0.55 seconds.

The error analysis of array measurements by Clay et al. (1973) describes the array gains in measurements of plane waves by arrays of K sensors as $K^{1/2}$ figure of merit for waveform estimation and K figure of merit for estimation of direction and the ray parameter ($dT/d\Delta$). Their analysis indicated that errors in direction and $dT/d\Delta$ for single incident plane waves are maximum likelihood estimates, if these parameters are measured by sensing the maximum beam power output of the ray given that the interfering noise is taken to be additive and Gaussian. They further showed that the array measurement errors can be reasonably well approximated as zero mean normal distributions if the arrays are sufficiently large. Clay's results were modified to account for signal generated noise and signal model anomalies by limiting the effective S/N of a single sensor. Bias in ray parameter, $dT/d\Delta$, and sensor time delays were assumed to be effectively removed. Therefore, zero mean Gaussian random variates were used to generate statistical deviations of direction and ray parameter from the expected transmission values, with the variance computed using our modification of Clay's formula which limits the S/N of a single sensor.

The signal loss is station measurement and configuration dependent and also site geology dependent. A first order approximation was used to derive the fractional decrease in the incident amplitude as proportional to the following factors:

- Square root of the number of sensors
- Average distance between adjacent sensors

- Ray parameter ($dT/d\Delta$)
- Dominant pulse frequency.

The constant of proportionality characterizing the array is input by the user as a station parameter. An array of relatively simple geology such as LASA would be characterized by a constant equal to 0.25; and of more complex geology such as NORSAR by 0.50.

## C. REMOTE FACILITY

The remote facility simulator is illustrated in Figure III-2. Subsystems represented are; the station detection processor (SDP), the remote storage element (RSE), and the data collection processor (DCP). The simulator functions as follows:

- Earth model imputs are converted to detection bulletins by the SDP
- Detection bulletins from the SDP are written on the RSE and stored for pickup by the communications processor
- Incoming waveform requests are written on the RSE and stored for processing
- The DCP reads waveform requests from the RSE and converts these to waveform messages
- Waveform messages are then written to the RSE for pickup by the communications processor.

Although the DCP simulation might include beamforming and generation of realistic waveform messages, because of time limitations the element is represented by a delay in converting waveform requests to waveform messages. The other two elements are discussed in this section.

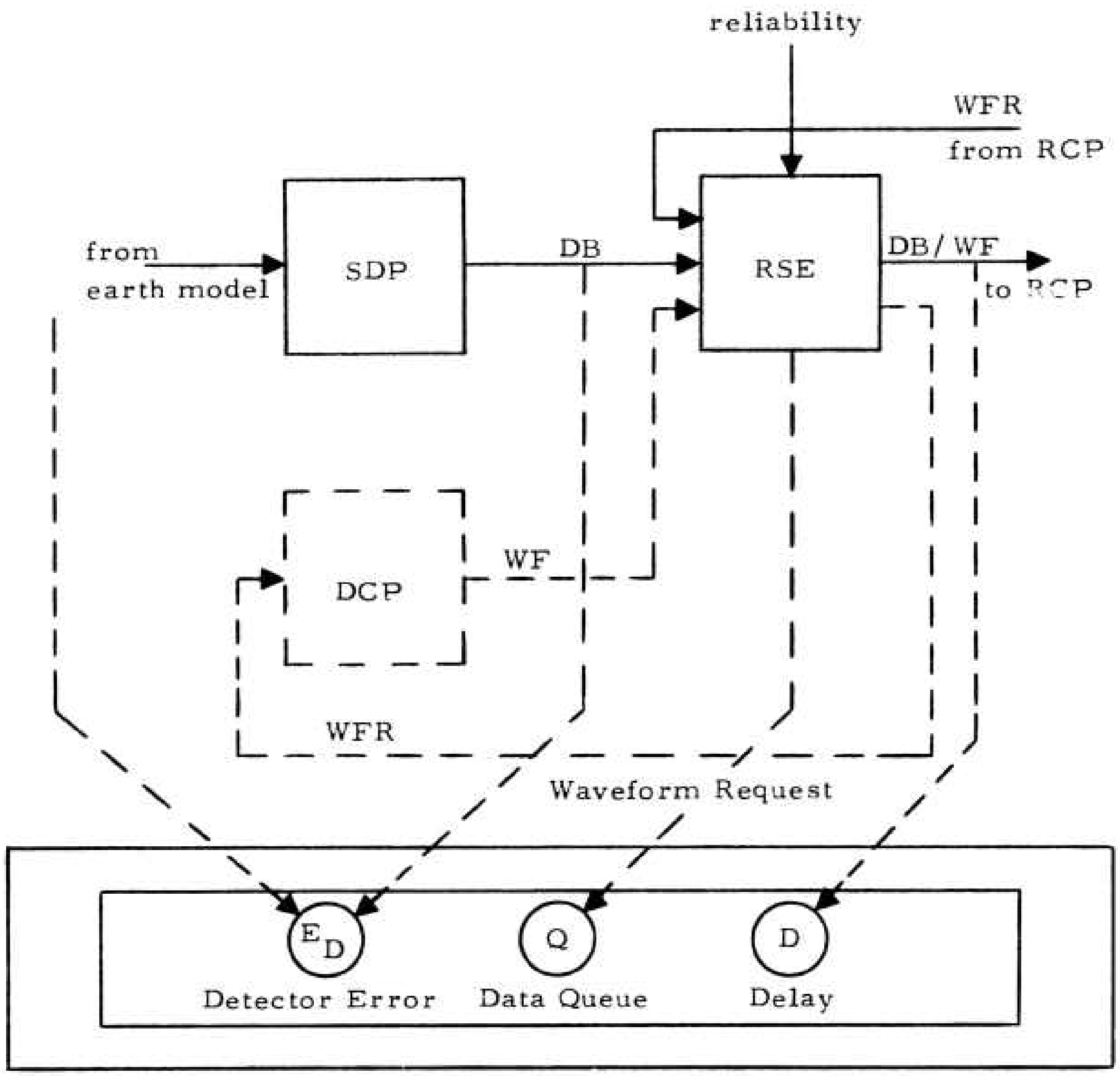



FIGURE III-2

BLOCK DIAGRAM OF THE REMOTE SIMULATOR

In Figure III-2, we should note the measurement points. These are:

- Detection error - This compares the known earth model inputs with the DB output stream for false alarms, missed events, and other types of errors.
- Data queues - These measure all queues at the RSE, i.e., WFR, DB, WF, and total data queues.
- Delay - This indicates the cumulative delay or age of the various messages as they are sent from the remote facility. The time tag is the arrival time of the originating DB.

Model descriptions for the remote facility are given next.

1. Station Detection Processor

The station detection processor detects possible seismic events. The detections are listed in a bulletin of event descriptions derived from the station measurements of the incident waves. The bulletins are sent to central headquarters to possibly be linked with other bulletins as indicative of a possible seismic source. The station detector is specified by the user by the following parameters.

- A threshold is imposed on $z = (x - \mu_n)/\sigma_n$, where $\mu_n$ is the updated noise mean estimate of detector noise, and $\sigma_n$ is the noise standard deviation. The detection variate $x$ is taken to be log A/T where A is the peak amplitude and T the corresponding period, and $z$ is assumed to be a zero mean unit normal variate for noise and $N(\mu_s - \mu_n, \sigma_s/\sigma_n)$ for signal.
- An ambiguity time gate is imposed upon maximum values of the detector measurements $x$ which exceed the threshold, in that

x must be the largest peak within the time gate preceding the possible event peak for all of the beams which are input into the detection gate.

The rules for simulating the occurrence of false alarms and the level of noise and signal are as follows:

- Independent log A/T fluctuations of short-period noise occur every 0.5 seconds.
- For each 0.5 second time slice within the detection gate, N statistically independent noise channels are transformed into N or less statistically independent beam channels. These are assumed to be nearly orthogonal transformations which preserve the number of statistical degrees of freedom.
- In each detection gate of K independent time fluctuations and of N independent beam estimates, the noise is taken conservatively as the maximum value of $K \cdot N$ independent trials.
- In each detection gate containing a seismic signal phase, the signal is conservatively taken as the realization of a single population detection trial.

The rules for simulating the automatic timing of first motion of a detection are as follows:

- Independent log A/T fluctuations of short-period signals occur at the dominant period of the signal limited by the short-period frequency response of the sensor.
- Coda statistics are generated with a single trial at the earliest detector time sample.

- Detection timing trials are sequential tests starting at the time of the peak log A/T measurement and backing off toward the beginning of the detector time interval.

- The first motion timing estimate is flagged when the log A/T realization is less than twice the mean noise. The alarm time is corrected for bias, based on S/N ratio by assuming a ramp from the start time.

- Simulated timing errors are based on signal log A/T fluctuation of $\sigma_s = 0.15$ magnitude units.

- Opportunities for false alarms occur from signal coda, interfering coda, and interfering events or phases.

The following information is included in the station detection bulletin:

- Identification of the station reporting

- Estimated arrival time

- Detectability measurement, $z = (x - \mu_n)/\sigma_n$
  - measurement of $x = \log A/T$; signal, noise or coda
  - updated mean noise, $\mu_n$
  - noise standard deviation, $\sigma_n$

- Ray parameter estimate, $dT/d\Delta$

- Direction estimate, $\theta$

- Ray parameter standard deviation of estimate

- Direction standard deviation of estimate.

The computer printout of the generated station bulletins occur in page blocks of 50. Along with the station bulletin itself, a unique detection bulletin index number is included for linkage of each detection to the DAP and other central facility lists generated by the system simulator. The event number is also printed to link the detection bulletin to the event list. Station bulletins are generated by simulating the station processors. The results are subjected to error analysis. The following list of errors is included in the bulletin list:

- Arrival time estimation error
- Azimuth direction measurement error
- Ray parameter, $dT/d\Delta$, measurement error.

In addition to error analysis of each detection bulletin, a set of status numbers are utilized to classify the results of detection processing. The following status information is given with each detection bulletin:

- Seismic phase identifier
- Interfering event flag specifying the event number of an interfering event. Zero indicates no interfering event
- Threshold status of signal and noise
  - ambient noise or coda dominant and below threshold
  - ambient noise dominant and above threshold
  - signal dominant and above threshold
  - signal dominant and below threshold
  - coda dominant and above threshold
- Detector performance diagnostic
  - indicates rank of signal, interfering event coda, if present, and ambient noise
  - indicates threshold status of signal and noise
- Detector automatic timing error diagnostic
  - picked a late arrival due to the signal's coda fluctuation

- picked an erroneous arrival due to an interfering event or phase
- picked an early arrival due to the interfering coda of a preceding event.

Table III-1 provides a detailed categorization of the state of the detector for each signal or false alarm encountered within the detection gate. The threshold status and diagnostic can be used to facilitate the counting of detection states to evaluate parts of or the entire system's performance under specified conditions.

The timing-error diagnostic flags correct timing or large timing errors as described in Table III-2. These can be associated with numerical timing errors and threshold status or diagnostic to completely evaluate an automatic first-motion timing algorithm.

2. Remote Storage Element

This model represents all storage at the remote facility. These are sensor data, detection bulletins, waveform requests and waveform messages. The simulation is accomplished without actually handling realistic files in two ways. First, the accumulated data is evaluated by a model involving a factor describing the storage requirements of a single detection bulletin. This is accumulated to arrive at a current file size at any time in the simulation. Second, bulletins and other messages to be communicated are represented by the bulletin arrival time. This results in a time lag for all messages in the system and is usually the only message identifier. The RSE model functions in the simulator as an interface between the remote facility and the communication facility by buffering messages until they are read by the relevant processor. The actual system may use a similar interfacing procedure since the processors may have a very small buffering capability.

TABLE III-1

DETECTION TRUTH TABLE

| Rank | | | Threshold | | | |
|---|---|---|---|---|---|---|
| Noise | Coda | Signal | $x > \tau$ | $s > \tau$ | Status | Diag-nostic |
| 2 | 1 or 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 1 or 0 | 0 | 1 | 0 | 1 | 1 |
| 1 | 0 | 2 | 0 | 0 | 3 | 3 |
| 1 | 0 | 2 | 1 | 1 | 2 | 2 |
| 2 | 0 | 1 | 0 | 0 | 0 | 6 |
| 2 | 0 | 1 | 1 | 0 | 1 | 5 |
| 1 | 2 | 0 | 0 | 0 | 0 | 0 |
| 1 | 2 | 0 | 1 | 0 | 4 | 4 |
| 3 | 1 or 2 | 1 cr 2 | 0 | 0 | 0 | 7 |
| 1 or 2 | 3 | 1 or 2 | 0 | 0 | 0 | 8 |
| 1 or 2 | 1 or 2 | 3 | 0 | 0 | 3 | 19 |
| 3 | 1 or 2 | 1 or 2 | 1 | 0 | 1 | 10 |
| 1 or 2 | 3 | 1 or 2 | 1 | 0 | 1 | 11 |
| 1 or 2 | 1 or 2 | 3 | 1 | 1 | 2 | 12 |
| 3 | 1 or 2 | 1 or 2 | 1 | 1 | 1 | 13 |
| 1 or 2 | 3 | 1 or 2 | 1 | 1 | 4 | 14 |

$x$ refers to threshold setting on log A/T measurement

$\tau$ refers to ambient noise or coda's log A/T value

TABLE III-2

TIMING ERROR DIAGNOSTIC

| Index | Code |
|---|---|
| 0 | Signal is not detected and timing not performed. |
| 1 | False alarm or coda is detected; false alarms timed anywhere and coda at the start time of time gate. |
| 2 | First motion timed data in the coda of the signal. |
| 3 | First motion timed erroneously in the coda of a preceding event which passes through entire time gate. |
| 4 | First motion timed in noise immediately preceding a gated interfering event. |
| 5 | First motion timed in coda of a gated interfering event. |
| 6 | First motion timed in noise immediately preceding signal first motion (normal case). |

The variables of the RSE model are summarized for reference purposes in Table III-3. The variables include four inputs and 26 states. The equations have a time step size of 15 seconds and were developed from a more detailed set at a step in the order of milliseconds representing access time and other micro-level operations. It was decided, however, that such detail was not desired for this element in the current simulator so the model was solved for the 15 second steps. This obviously reduces the operations to an immediate turn-around in the 15 seconds and simplified the model. The model may be characterized further by the remarks given below for each of the major states.

- A DB is sent if the DB read command is on (=1) and its serial number is that of the first or oldest message on the DB queue
- A WF message is sent if the WF read command is on. It takes the serial number of the first or oldest message on the WFR queue
- The DB buffer is updated from its last state by the SDP, input DB serial number and the RCP read command
- The WFR buffer is updated from its last state by the RCP, WFR write and WF read command.

Buffer and reliability models are discussed in subsection III-F, Auxiliary Models.

## D. COMMUNICATIONS

A block diagram of the communications facility simulator is given in Figure III-3. The elements modeled are: the remote communications processor (RCP), the international communications channel (ICC), and the central communications processor (CCP). The communications system from each

TABLE III-3

SUMMARY OF THE RSE MODEL VARIABLES

| | |
|---|---|
| **Inputs (SDP to RSE)** | |
| U(2, k) | = Detection Bulletin serial number or the arrival time |
| **Inputs (RCP to RSE)** | |
| U(12, k) | = Detection bulletin read command |
| U(13, k) | = WFR serial number write |
| U(14, k) | = WF read command |
| **Parameters** | |
| Y(1) | = MTBF in hours |
| Y(2) | = MTTR in minutes |
| Y(3) | = DB maximum queue length |
| Y(4) | = WFR maximum queue length |
| **Feedforward States (RSE to RCP)** | |
| X(3, k) | = Output detection bulletin serial number |
| X(4, k) | = Output waveform serial number |
| **Feedback States (RSE to SDP)** | |
| X(11, k) to X(20, k) | = not used |
| **Internal States** | |
| X(23, k) | = Cumulative data in 16 bit words |
| X(24, k) | = DBSN queue input index |
| X(25, k) | = WFSN queue input index |
| X(31, k) to X(40, k) | = DB queue |
| X(41, k) to X(50, k) | = WFR queue |

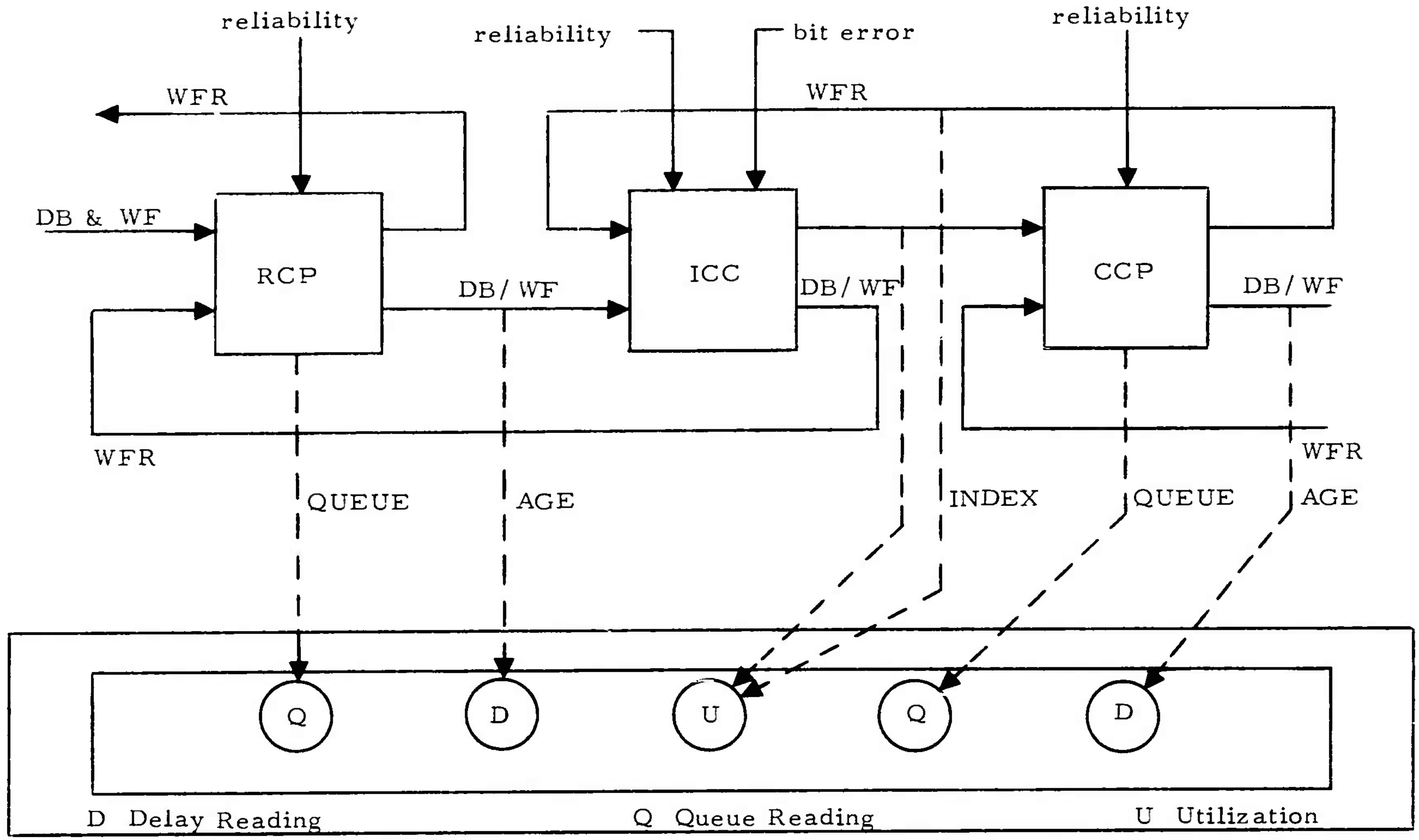



FIGURE III-3

BLOCK DIAGRAM OF THE COMMUNICATIONS FACILITY station is assumed to have the same general organization and models, but perhaps with different parameter settings such as the bit rate parameter.

The flow of information starts at the left of this figure. The RCP reads any detection bulletins which have been placed on the RSE. Messages are stored on a small RCP buffer awaiting an exchange command from the CCP. When this occurs, outgoing messages are picked up by the ICC and after a delay are available to the CCP. The ICC may insert a block error flag into the outgoing message depending on random variables. The CCP receives incoming messages and writes these to a central facility storage element provided no errors are detected. If a block error is detected, the CCP asks for a retransmission of the block. Also, CCP reads messages going to the field from the central facility. At the completion of an incoming message, CCP transmits messages addressed to the remote facility. Back messages are received by the RCP and either retransmitted in the case of an error, or stored in the case of an error-free message.

The models to be described include the communications protocol since this is a major factor in the effective line capacity of the communications system. In particular, the models simulate the Advanced Data Communications Control Procedure (ADCCP) developed by the American National Standards Institute (1973). In accordance with this procedure, the CCP is given the roll of the 'primary' processor and the RCP the roll of the 'secondary' processor. For convenience, a number of features of the standard recommended by Sax et al., (1974) were omitted from the simulator or simplified. One simplification of importance was the substitution of a stop-and-wait error control procedure for the continuous error control procedure. Without getting into the details, the effect is that the simulated capacity is slightly less than the capacity which would result from the recommended procedure. However, equations are available (Abramson and Kuo, 1973) for estimating the correct capacity for a full-duplex system.

Because the ADCCP control messages are eight bits in length, the communications simulator step size is 0.15 seconds for a 50 bps line, i.e.,

8 bits/50 bits/second = 0.15 seconds.

As a result, to develop long-term statistics, either the model must be solved for larger steps or an empirical model developed to fit samples from the simulator micro-model.

The major statistics developed by the communications simulator are:

- Queue measures - These are taken on DB's, WF's and WFR messages at the RCP and CCP processors
- Delay measures - These are taken at the output of each processor by subtracting the message time tag from the current simulated time
- Utilization - This measurement is of the number of times a channel or processor is in use divided by the total number of times the line is sampled.

1. Remote Communications Processor

The remote communications processor (RCP) model consists of 13 input variables and 50 state variables. These are defined in Table III-4. A total of eight parameters are available for modifying the model through input data cards. Additional modifications can be made by altering the state equations. The state equations are described below in the order given in Table III-4 beginning with the feedforward states (RCP to ICC):

- The RCP signals a block error whenever the input message contains an error or if the CCP asks for retransmission of the last message and this was the block error signal

TABLE III-4

SUMMARY OF THE RCP MODEL VARIABLES
(PAGE 1 OF 2)

| | | |
|---|---|---|
| **Inputs (RSE to RCP)** | | |
| U(3, k) | = | DB serial number |
| U(4, k) | = | WF serial number |
| **Inputs (ICC to RCP)** | | |
| U(11, k) | = | Error on last block |
| U(12, k) | = | Exchange |
| U(13, k) | = | Request status |
| U(14, k) | = | Reset |
| U(15, k) | = | End of block flag |
| U(16, k) | = | Poll |
| U(18, k) | = | Error on incoming block |
| **Parameters** | | |
| Y(1) | = | MTBF in hours |
| Y(2) | = | MTTR in minutes |
| Y(3) | = | DB queue maximum length |
| Y(4) | = | WF queue maximum length |
| Y(5) | = | WFR |
| Y(6) | = | Block size in bits |
| Y(7) | = | DB length in 16 bit words |
| Y(8) | = | WF length in 16 bit words |
| Y(9) | = | MTBF random number |
| Y(10) | = | MTTR random number |

TABLE III-4

SUMMARY OF THE RCP MODEL VARIABLES

(PAGE 2 OF 2)

| | |
|---|---|
| **Feedforward States (RCP to ICC)** | |
| X(1, k) | = Error on last transmission (NAFC) |
| X(2, k) | = Acknowledge with information (ACWI) |
| X(3, k) | = Accept (ACPT) |
| X(4, k) | = Status ready receive, ready send (STRS) |
| X(5, k) | = Status no receive or send (STNN) |
| X(6, k) | = Output DB serial number (DB) |
| X(7, k) | = Output WF serial number (WF) |
| X(8, k) | = Flag |
| **Feedback States (RCP to RSE)** | |
| X(12, k) | = Send detection bulletin |
| X(13, k) | = Waveform request serial number |
| X(14, k) | = Send waveform |
| **Internal States** | |
| X(21, k) | = Waveform request counter |
| X(22, k) | = Interface counter |
| X(23, k) | = Block counter |
| X(24, k) | = Detection bulletin word counter |
| X(25, k) | = Waveform word counter |
| X(26, k) | = DBSN queue input index |
| X(27, k) | = WFSN queue input index |
| X(28, k) | = WFRSN queue input index |
| X(31, k) to X(40, k) | = DB queue |
| X(41, k) to X(45, k) | = WF queue |
| X(46, k) to X(50, k) | = WFR queue |
| X(51, k) to X(59, k) | = Output state memory |

- At the completion of a good reception by RCP, an acknowledgment is sent. Also an acknowledgment is sent if a retransmission request is received and this was the last message

- An accept signal is sent if a reset command is received or if a retransmission is requested and this was the last message.

After the above response, the program should zero all RCP states.

- A status-ready signal is sent if a request-status command is received and RCP has space on its buffers for at least one WFR message

- A status-not-ready signal is sent if a request-status command is received and the RCP cannot, for the moment, buffer another waveform request or if a retransmission is requested and this was the last message

- A detection bulletin begins to be sent when the last output was acknowledged with information and if there is at least one bulletin on the detection bulletin queue. It continues to be sent until a bulletin word counter signals that all words have been sent without error or continues to the end of a block whichever is sooner

- A waveform message starts or resumes transmission after an acknowledgment with information is sent and if a message is on the WF queue and none on the DB queue. Transmission continues until all WF words have been sent without error or until the end of a block whichever is sooner.

We note that the last two steps determine that DB's have priority over WF messages. If a DB arrives when a WF transmission has started, it must wait until the end of the WF block.

- An end-of-block flag is sent if either the block counter pulses on or if the message word counter pulses on in the case where message length is less than a block.

This ends the feedforward equations. The next set of equations apply to signals sent to the RSE which simulate interfacing with a disk unit by read or write commands.

If disk access is time divided, then the interface time signals the start of the RCP time segment. It is also used to interface the models which are simulating at different time steps.

- A receive WFR command or disk write is sent when the interface counter pulses on given that the WFR queue contains at least one message
- A sent DB command (or WF) is sent when the interface counter pulses on and if the DB queue (or WF queue) is not full.

The following states are internal to the RCP and are used to support or control the output states:

- The WFR word counter is indexed upward by the transmission of a WFR word and indexed downward by the lesser of a block or the message length upon detection of an error in the last input block. The counter goes to zero after indexing to the message length without error
- The interface counter simply indexes up to the interface time limit then resets to zero
- The block counter indexes for each word sent until reaching the block limit and resets to zero

- The DB word counter indexes upward for each word sent and downward by the lesser of a block or the message length when the last message was a DB and an error was detected by the CCP

- Similarly, the WF word counter indexes up when a word is sent and down by the lesser of block or message length when the last transmission was a WF block and an error was detected by the CCP. It resets to zero when the last transmission was a WF block followed by the CCP primary-acknowledge signal.

The first three relations below make use of a 'buffer function' which is discussed later:

- The DB queue or buffer vector is shifted up first-in first-out (FIFO) fashion when the last message sent was a DB word and a primary-acknowledge signal was received from the CCP. The input command is on when a DB is read from disk and that message is placed at the end of the queue

- Similarly, the WF queue or buffer vector is shifted up FIFO fashion when a primary-acknowledge is received from the CCP and the last message sent was a WF message

- The WFR queue is shifted up when a WFR message is sent to the RSE disk and down when a WFR message is received without error from the CCP

- Output states to the CCP are stored until a response is received from the CCP and updated by the resulting state

- It is convenient to store the WFR number when one is being received. This is entered on the WFR queue on the next iteration after checking for an error.

2. International Communications Channel

The major functions of this model are to simulate the message delay, the bit errors, and the failure behavior of the leased communications lines. For such 'long-haul' communications the delay is between 0.5 and 2 seconds, the bit error probability is $10^{-3}$ to $10^{-6}$, the failure rate is 1 to 2 failures per year and repairs take 2 to 5 minutes to switch to alternate routing.

The model variables are listed in Table III-5. We see that the model contains two input vectors, an 200 x 1 state vector and four parameters. The parameters are reliability, maintainability, delay time, and bit error probability.

A transition function (SHIFT) merely transfers all messages on the line 0.15 seconds closer to the output position, thereby updating the communications line status. The function is documented in the subsection entitled 'Auxiliary Models,' is convenient for solving larger time steps but may be better implemented by shifting pointers rather then the messages.

When a message leaves the channel, a test is made for an end-of-block flag and if the test is true, another test is made for a block error. A binomial probability is assumed for generating the block errors. Burst errors, common in long-haul systems can be simulated by setting a high bit error probability, say $10^{-1}$, for a period. An error flag is inserted in the 10th position of the output message if this test is passed.

3. Central Communications Processor

It was stated in the introduction to this section, that the CCP was the primary processor of the communications system. This is reflected in the model to be described where the output variables are more command oriented than those of the RCP and the equations are somewhat more complex.

TABLE III-5

SUMMARY OF THE ICC MODEL VARIABLES

| | | |
|---|---|---|
| UA | = | Input eight word vector (RCP to CCP) |
| UB | = | Input eight word vector (CCP to RCP) |
| X | = | Delay vector for inputs |
| Y(1) | = | Channel MTBF (approximately 4000 hours) |
| Y(2) | = | Channel bit error rate |
| Y(3) | = | Channel MTTR (approximately 2 minutes) |
| Y(4) | = | Channel delay in seconds (approximately 1 second) |
| Y(5) | = | Block size, bits |
| Y(6) | = | MTBF random number |
| Y(7) | = | MTTR random number |
| Y(8) | = | Bit error random number |

Time step T = 0.15 seconds for 50 B/S and 8 Bit words

Since the CCP commands all RCP's, some procedure is needed for accessing the CCP such as time division or parallel access. The present simulator interfaces with just one CCP so that the access procedure needs to be taken into account by the calling routine of the simulator. With this approach various access procedures can be simulated, possibilities are - all stations to one CCP, each station to a different CCP, several stations to one CCP, sequential or parallel.

Table III-6 lists the variables of the model and their definitions. We note that there are 12 input variables and 50 state variables. In words, starting with the feedforward states (CCP to CSE), the simulator performs as follows:

- At intervals determined by an interface counter, the first message on the DB queue is sent to the CSE i.e., written on the central facility disk
- In the same time step, the first WF message on the WF queue is sent to the central facility disk
- Also, in the above time step, a WFR read command is sent to the CSE, i.e., the CCP reads disk for a WFR message.

This is all of the outputs to the central facility. The following messages are sent to the remote facility (CCP to RCP):

- A block error message is sent if an error occurs in the input message or in response to a retransmit request if the last message sent was a block-error message
- An exchange command is sent if RCP has sent a status-ready message, given that CCP is not in the process of sending a WFR message. It also sends the exchange message in response to a retransmit request if it applies

TABLE III-6

SUMMARY OF THE CCP MODEL VARIABLES
(PAGE 1 OF 2)

| | | |
|---|---|---|
| **Inputs (ICC to CCP)** | | |
| U(1, k) | = | Error on last CCP transmission (NAFC) |
| U(2, k) | = | Acknowledge with information (ACWI) |
| U(3, k) | = | Accept (ACPT) |
| U(4, k) | = | Status - ready receive, ready send (STRS) |
| U(5, k) | = | Status - not ready receive or send (STNN) |
| U(6, k) | = | DB input |
| U(7, k) | = | WF input |
| U(8, k) | = | End of block flag (FLG) |
| U(10, k) | = | Error in received RCP message (ERR) |
| **Inputs (DAP to CCP)** | | |
| U(12, k) | = | Waveform request serial number |
| **Parameters of CCP** | | |
| Y(1) | = | Block size, bits |
| Y(2) | = | MTBF (approximately 8000 hours) |
| Y(3) | = | MTTR (approximately 120 minutes) |
| Y(4) | = | Maximum DB buffer length |
| Y(5) | = | Maximum WF buffer length |
| Y(6) | = | Maximum WFR buffer length |
| Y(7) | = | MTBF random number |
| Y(8) | = | MTTR random number |
| Y(9) | = | DB length, 16 bit words |
| Y(10) | = | WF length, 16 bit words |
| **Feedforward States (CCP to DAP)** | | |
| X(3, k) | = | Detection bulletin serial number |
| X(4, k) | = | Waveform serial number |
| X(5, k) | = | Send waveform request command (0, 1). |

TABLE III-6

SUMMARY OF THE CCP MODEL VARIABLES
(PAGE 2 OF 2)

| | | |
|---|---|---|
| **Feedback States (CCP to ICC)** | | |
| X(11, k) | = | Error on last RCP transmission (NAFC) |
| X(12, k) | = | Exchange (EXCHR) |
| X(13, k) | = | Request status (RQBS) |
| X(14, k) | = | Reset (RSET) |
| X(15, k) | = | Block flag (FLG) |
| X(16, k) | = | Poll (POLR) |
| X(17, k) | = | Primary acknowledge (PACK) |
| X(18, k) | = | Output serial number |
| **Internal States** | | |
| X(22, k) | = | WFR word counter |
| X(23, k) | = | Interface counter |
| X(24, k) | = | Detection bulletin word counter |
| X(25, k) | = | Waveform word counter |
| X(26, k) | = | DB queue input index |
| X(27, k) | = | WF queue input index |
| X(28, k) | = | WFR queue input index |
| X(29, k) | = | Response timer |
| X(31, k) to X(40, k) | = | DB queue |
| X(41, k) to X(45, k) | = | WF queue |
| X(46, k) to X(50, k) | = | WFR queue |
| X(51, k) to X(58, k) | = | Output state memory |
| X(59, k) to X(60, k) | = | Input memory |

- The status of the RCP is requested if there has been no response within a time interval determined by a response timer ($\sim$ 3 seconds), or if an end-of-block flag is received and an error is not detected, or if a retransmission is requested and this was the last message sent.

The reset and poll commands are not used in the current simulator, but may be actuated by an operator command if interactive simulation is desired.

- An end-of-block flag is sent immediately after the exchange command if no WFR messages are on the queue, or upon completion of a WFR transmission or a block of this transmission whichever occurs first

- A primary acknowledge signal is sent if an error free message is received

- A WFR word is sent immediately after the exchange command if a WFR is on the WFR queue and words continue to be sent until the end of a block is reached or all words have been sent correctly.

The remaining states are internal to the CCP:

- The WFR word counter starts when a WFR word is sent and continues until a block is sent or until the entire message is sent if the message is less than a block

- The interface counter counts up to a time limit parameter which determines the frequency of interfaces with the central facility disk

- The DB word counter sums the number of DB words received in a message and subtracts the lesser of a block or the message length in the case of a transmit error

- Similarly, the WF word counter sums the number of WF words received and subtracts the lesser of a block or the message length when an error is received
- The response timer starts immediately after CCP sends a message and counts up to a response time limit if no reply is received or resets to zero if a reply is received.

The remaining state equations pertain to buffers which function as in the RCP model.

To summarize the attributes of the communications facility simulator, it:

- Simulates the Advanced Data Communications Control Procedure
- Assumes the CCP is the only primary processor in the network
- Assumes that all RCP's are secondary processors
- Assumes that leased lines are half-duplex, permitting transmissions one-way at a time
- Simulates a stop-and-wait error control procedure
- Operates all buffers on a first-in first-out basis
- Interfaces with the other facilities by disk
- Contains parameters for designating line rate, response time, message sizes, buffer sizes, and interface frequency.

## E. CENTRAL FACILITY

Figure III-4 is a block diagram of the central facility simulator. Three elements are shown, these are; the central storage element (CSE), the detection association processor (DAP), and the event classification processor (ECP). Operator elements (OP) are shown which may control several inputs

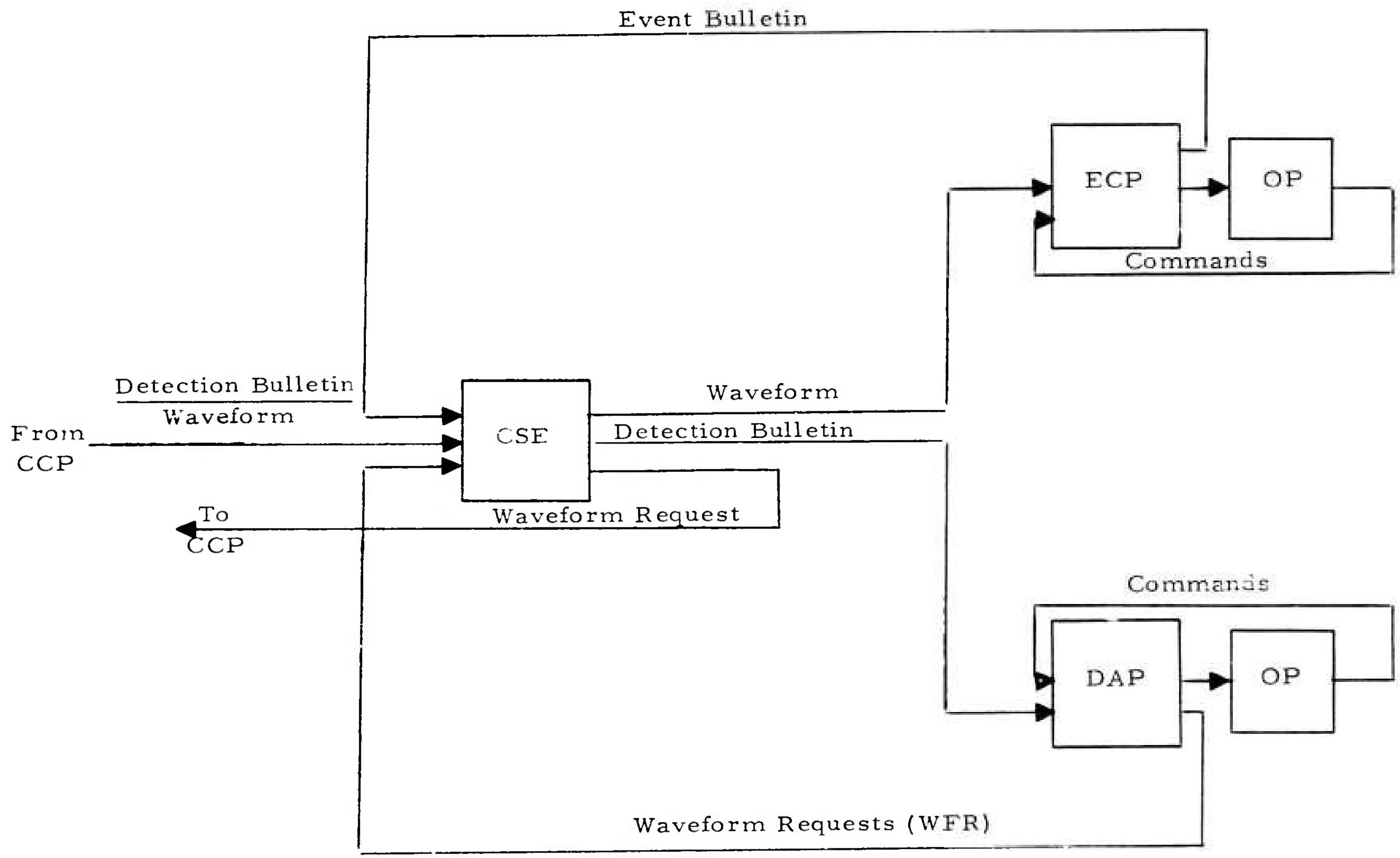



FIGURE III-4

CENTRAL FACILITY SIMULATOR

if interactive simulation is desired. The general purpose of the CSE is to store all data at the central facility and to interface the processors with the communications processor. The DAP has the function of associating DB's from the separate stations and generating WFR messages containing an estimated event location and origin time. The ECP treated as a delay in the present simulator, has the function of taking the resulting WF data and performing the final processing for the network decisions. Since it is the last element in the on-line system, the simulated delay may be added to the cumulative time to receive WF messages. This subsection presents the two simulated elements, beginning with the CSE.

1. Central Storage Element

This element simulates the dominant behavior of the central facility disk units. It handles the three types of data sets, DB's, WFR's, and WF's, as they are transmitted into or out of the central facility. Table III-7 summarizes the variables used in the model. Since the communications simulator does not actually transmit messages but only message serial numbers, the CSE stores only these numbers and the number of the originating station. When messages are forwarded to the DAP the actual message (DB) is retrieved from tape and provided to the DAP simulator. This procedure is reflected in the variable definitions where there are only six input variables, three from the CCP and three from the DAP. The CSE has ample storage for the abbreviated messages as can be seen from the 80 state variables, 60 of which are simply storage positions for the stations numbers and message serial numbers. Also, the model provides five design parameters pertaining to reliability and maximum file sizes.

The state equations, beginning with the feedforward states, may be described as follows:

TABLE III-7

SUMMARY OF THE CSE MODEL VARIABLES
(PAGE 1 OF 2)

| | | |
|---|---|---|
| **Inputs (CCP to CSE)** | | |
| U(3, k) | = | Detection bulletin serial number write |
| U(4, k) | = | Waveform serial number write |
| U(5, k) | = | Waveform request read command |
| **Inputs (ECP or DAP to CSE)** | | |
| U(12, k) | = | Waveform request serial number write |
| U(13, k) | = | Detection bulletin read command |
| U(14, k) | = | Waveform read command |
| **Parameters of CSE** | | |
| Y(1) | = | Mean time between failure, hours |
| Y(2) | = | Mean time to repair, minutes |
| Y(3) | = | DB queue maximum length, messages |
| Y(4) | = | WF queue maximum length, messages |
| Y(5) | = | WFR queue maximum length, messages |
| Y(6) | = | MTBF random numbers |
| Y(7) | = | MTTR random numbers |

TABLE III-7

SUMMARY OF THE CSE MODEL VARIABLES
(PAGE 2 OF 2)

| | |
|---|---|
| **Feedforward States (CSE to DAP or ECP)** | |
| X(1,k) | = Detection bulletin station address |
| X(2,k) | = Detection bulletin serial number |
| X(3,k) | = Waveform station address |
| X(4,k) | = Waveform serial number |
| **Feedback States (CSE to CCP)** | |
| X(11,k) | = Waveform request station address |
| X(12,k) | = Waveform request serial number |
| **Internal States** | |
| X(21,k) to X(30,k) | = DB station number queue |
| X(31,k) to X(40,k) | = DB serial number queue |
| X(41,k) to X(50,k) | = WF station number queue |
| X(51,k) to X(60,k) | = WF serial number queue |
| X(61,k) to X(70,k) | = WFR station number queue |
| X(41,k) to X(80,k) | = WFR serial number queue |

- A DB station number is sent if a DB read command is received from the DAP, and this is taken from the first DB on the DB station number queue
- A DB message number is sent if a DB read command is received from the DAP, and this is taken from the first value on the DB serial number queue
- Similarly, the oldest WF station number and message number are sent if a WF read command is received from the DAP or ECP.

The following describes the feedback states (CSE to CCP):

- Both the oldest WFR address and serial number are sent to the CCP if the WFR read command is received.

The internal states represent memory. For this, the buffer function is used as in the RSE model in subsection III-D-1.

2. Detection Association Processor

Being a significant network element, the DAP is simulated in greater detail than the previous elements. As shown in Figure III-5 the DAP consists of four models named: the DAP control unit (DAPC), the DAP associator (DAPA), the DAP locator (DAPL), and the DAP output unit (DAPO). The major units are the DAPA and the DAPL since these are concerned with the association and location aspects of the DAP in order to remove operations which are not an important part of the major units from those routines.

To explain the flow in this diagram, the first unit the DAPC has the functions of reading DB's from the CSE, and when a sufficient number have been read into the work space, DAPC 'enables' the major units. The next step is to develop a single-station location and origin time estimate. This is done

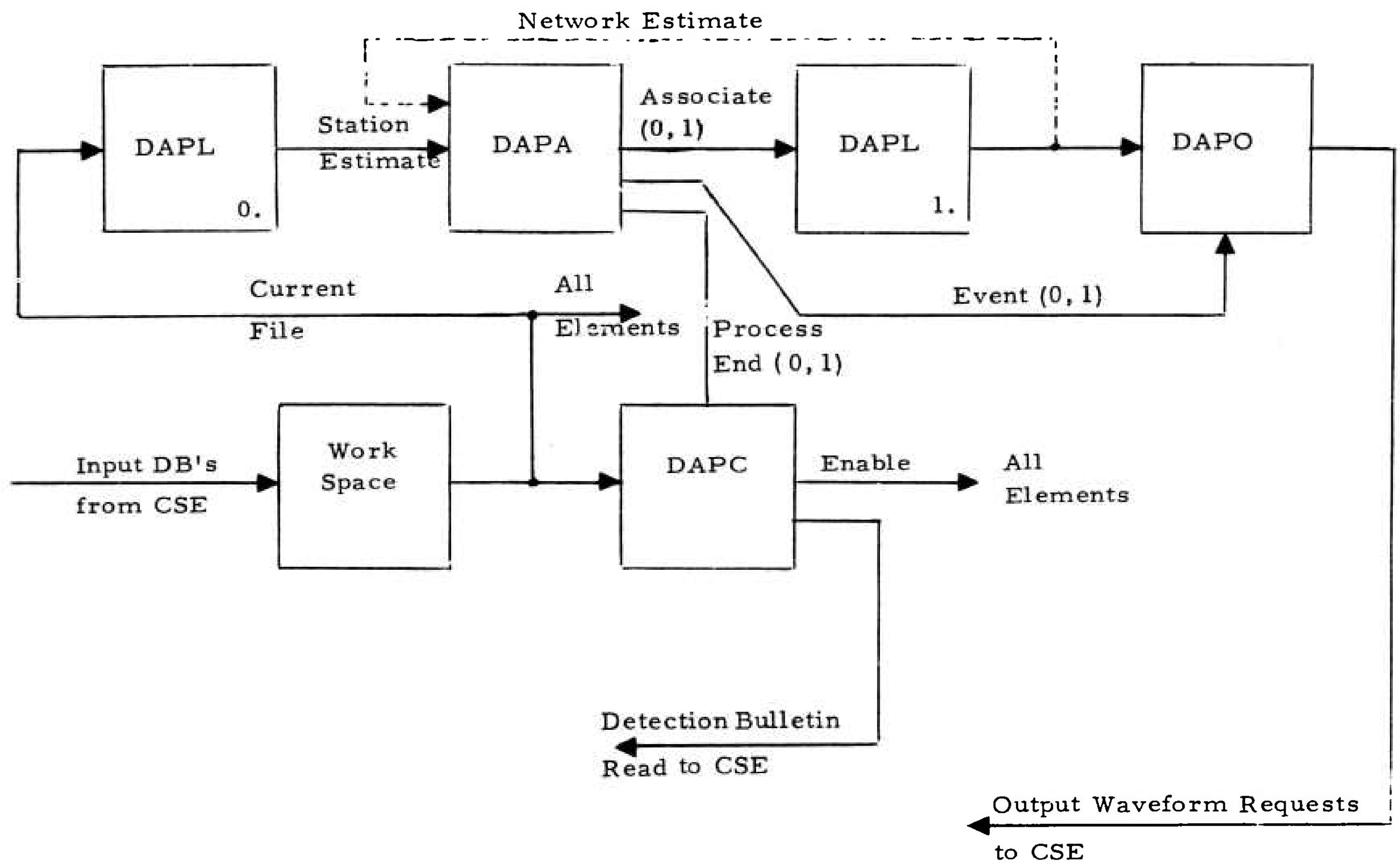



FIGURE III-5

DETECTION ASSOCIATION PROCESSOR SIMULATOR by DAPL operating in 'mode 0'. Also the estimate variances are computed for use in the association step. Then, the DAPA checks for the truth of a number of conditions which need to be met by a DB to have a correct association, compared with a key bulletin. After an associate is found, DAPL operating in 'mode 1' calculates a network location estimate for use in the next association. The association and location procedures are discussed in the following paragraphs. The final unit, DAPO, checks the DAPA output to see if an event has been declared and if so generates a WFR message and clears the associates from the DAP work space then control returns to the DAPC unit.

Table III-8 summarizes the DAP model variables. Ten inputs are shown, these are the DB items being read into the work space at the time step k. The model has 6 design parameters that describe; the station locations, reliability and maintainability of the DAP, the work space size and finally, the bulletin size. States of the model are broken down by the different DAP units.

The control unit, DAPC, has three states having the definitions shown in this table. The equations may be described as follows:

- A DB is read if the system is not enabled for processing and if the DB work space is not full at the input position

- The enable timer counts up to a time limit for the DAP to wait for new information. It indexes upward if all key levels have been processed, if it has not already reached its limit, and if no new bulletins are read in. It resets to one if a new bulletin is read in

- The DB counter operates when the processor is not enabled, counting upward when a DB is received and resetting to zero when the system is enabled.

TABLE III-8

DAP MODEL VARIABLES
(PAGE 1 OF 2)

| | |
|---|---|
| **Inputs (CSE to DAP)** | |
| U(1, k) | = Station ID |
| U(2, k) | = DB serial No. or arrival time |
| U(3, k) | = Event magnitude estimate or z-statistic |
| U(4, k) | = Event magnitude estimate standard error (not used) |
| U(5, k) | = Event origin time estimate (not used) |
| U(6, k) | = Event azimuth estimate |
| U(7, k) | = Event ray estimate |
| U(8, k) | = Arrival time estimate error |
| U(9, k) | = Azimuth estimate error |
| U(10, k) | = Ray estimate error |
| **Inputs (from operator to DAP, not used)** | |
| **Parameters** | |
| Y(1) | = Mean time between failures, hours |
| Y(2) | = Mean time to repair, minutes |
| Y(3) | = MTBF random number |
| Y(4) | = MTTR random number |
| Y(5) | = Work space limit in number of DB's |
| Y(6) | = Number of items on a detection bulletin |
| Y(i) | = Station latitudes, i = 16, . . . , 40 |
| Y(i) | = Station longitudes, i = 41 , . . . , 65 |
| **Feedforward (To operator or ECP)** | |
| X(1, k) to X(10, k) | = Single station location estimates and variances. (DAPL) |

TABLE III-8

DAP MODEL VARIABLES
(PAGE 2 OF 2)

| | | |
|---|---|---|
| **Feedback (DAP to CSE)** | | |
| X(11, k) | = | WFR address (DAPO) |
| X(12, k) | = | WFR number (DAPO) |
| X(13, k) | = | Send DB (DAPC) |
| X(15, k) | = | Event bulletin number (DAPO) |
| X(16, k) to X(20, k) | = | not used |
| **Internal States** | | |
| X(21, k) | = | Key in progress (DAPA) |
| X(22, k) | = | Key index (DAPA) |
| X(23, k) | = | File index (DAPA) |
| X(24, k) | = | Event counter (DAPA) |
| X(25, k) | = | Association counter (DAPA) |
| X(27, k) | = | Enable timer (DAPC) |
| X(28, k) | = | DB counter (DAPC) |
| X(31, k) | = | Network magnitude estimate (DAPL) |
| X(32, k) | = | Network time estimate (DAPL) |
| X(33, k) | = | Network latitude estimate (DAPL) |
| X(34, k) | = | Network longitude estimate (DAPL) |
| X(36, k) | = | Network magnitude estimate error variance (DAPL) |
| X(37, k) | = | Network origin time estimate error variance (DAPL) |
| X(38, k) | = | Network latitude estimate error variance (DAPL) |
| X(39, k) | = | Network longitude estimate error variance (DAPL) |
| X(41, k) to X(50, k) | = | Associate address (DAPO) |
| X(51, k) to X(60, k) | = | Associate WFR serial number (DAPO) |
| X(101, k) to X(200, k) | = | Input work area |

Once the major units are enabled, control passes first to the locator DAPL operating in mode zero. The processing may be described as follows:

- A single-station estimate of location and origin time is developed as the expected value of these given the information on a single bulletin
- Along with the above estimate, an estimate is made of the location and origin time error covariance. This is used to develop the error ellipsoid used in association.

The above operations are performed on all DB's in the work space. After this control starts the associator, DAPA.

The associator applies a key station and error ellipsoid technique. Keying implies that a bulletin parameter such as the signal-to-noise ratio or z-statistic is used to order the bulletins from best to worst as they are associated. Afterwards, this parameter is used to update a network location estimate. The best station, the first to pass the highest keying threshold, is referred to as the 'key station'.

The first association attempt is between the key station and the next-best station. Several association tests are performed, the most important of which is the 'error-ellipse' test. This is similar to a t-test, i.e., for significant differences between means having unequal variances. Means in our test are the estimates of latitude, longitude, and origin time (referred to as the location). The variances are the estimate errors covariance (matrix). The algorithm being simulated is summarized in Table III-9. Another test is for the distance between the station and the event. All tests are controlled by parameters in the simulator. The following is a description of the DAPA state equations:

TABLE III-9

ASSOCIATION ALGORITHMS

| Definitions | | |
|---|---|---|
| $\hat{X}_{(S,i)}$ | = | Single station location estimates for the i-th station. |
| $V_{\tilde{X}(S,i)}$ | = | Error covariance matrix for the above estimate. |
| $\hat{X}(N,K)$ | = | Network location estimate after K stations have been associated. The first is the key station estimate. |
| $V_{\tilde{X}(N,K)}$ | = | Error covariance matrix for the above estimate. |
| n | = | A number of standard deviations along the error ellipsoid independent axis, i.e., a probability contour. |
| X(A) | = | A point whose existance on both ellipsoids implies association. |

| Test Algorithms | |
|---|---|
| Association Test Point | $X(A) = \left(V^{-1}_{\tilde{X}(N,K)} + V^{-1}_{\tilde{X}(S,i)}\right)^{-1} \cdot \left(V^{-1}_{\tilde{X}(N,K)}\hat{X}(N,K) - V^{-1}_{\tilde{X}(S,K)}\hat{X}(S,i)\right)$ |
| Association Test | $F = \begin{cases} 1, & \text{if the following is true} \\ 0, & \text{otherwise} \end{cases}$<br>$(X(A) - \hat{X}(N,K))^T V^{-1}_{\tilde{X}(N,K)}(X(A) - \hat{X}(N,K) \leq n^2$<br>and<br>$(X(A) - \hat{X}(S,i))^T V^{-1}_{\tilde{X}(S,i)}(X(A) - \hat{X}(S,i)) \leq n^2$ |

- A key in progress is indicated if it was not previously 'on', if a combined association test is true, and if all key index levels have not been processed

- A key index, which sets quality levels for acceptance of bulletins as the best to key on, indexes upward after the entire file (work space) has been scanned and it resets to one after all key levels have been searched

- The file index merely counts up the file length (10 DB's) and then resets to the first file position. It indexes with each entry to DAPA

- The event counter counts the number of events having been declared by the DAP. It indexes when all processing is completed on that event

- The association counter sums the number of associates found for the current key. It resets to zero after all bulletins have been tested against the current key.

Note that DAPA operates on one DB with each entry. After its completion, if an association was true, the network estimate is updated otherwise DAPA is reentered. If an association is made, DAPL (mode 1) is enabled. In mode 1, the procedure is:

- A network estimate is developed from the last network estimate and the current (associated) DB by computing the expected value given all associated bulletins up to and including the current one

- A resultant (a posteriori) error covariance matrix for the above estimate is computed for use in association if desired.

The approach used to develop the above estimate is not so much the subject of the system simulation at this time. But the method should be a reasonable approximation of the expected values since this is the alternative being simulated. In the present simulator, a nonlinear Kalman filter is used having the observations arrival time, ray, azimuth, and their variances. This method was selected because much of the software was on hand.

If an event is declared, the output unit, DAPO, is enabled. Its function is to develop waveform requests to stations within 110° of the event location, and to clear the associates from the DAP workspace.

## F. AUXILIARY MODELS

Three functions used in the previous elements are the buffer function (BUFF), the propagation function (SHIFT), and the reliability function. Their models are described in this subsection. The models may be used in solving elements for larger time steps and the mathematics for analysis of element responses.

### 1. Buffers

A general purpose buffer model is used to simulate the FIFO buffer action of several elements for analysis purposes. The model is not intended to be a prescription for implementing such a buffer.

The operating features of the model are:

- When an input data point is received, it is placed at the end of the queue as indicated by the index
- When an output command is received, the first or oldest data point is removed from the front of the queue

- Simultaneous input and output commands are permitted. After commands are executed, the index is shifted forward, backward, or not shifted as appropriate.

Figure III-6 illustrates the three data points 3.50, 4.25, and 5.00, which may represent detection arrival times, as they would appear on this buffer.

2. Propagation

The function (SHIFT) simulates the propagation along a coordinate of the values in the state vector. It may be used to represent propagation in discrete distributed processes or a shift register. The program form is:

CALL SHIFT (state vector, input vector, input position, cycle option, erase option).

The operations of the SHIFT function may be described as follows:

- The input vector inserted into the old state vector at the input position
- The current and all previous input vectors are shifted one vector length toward the end of the register
- If the cycle option is selected, the oldest input vector is removed from the end of the register and placed at the beginning
- If the erase option is selected, the oldest input vector is erased and zeros are inserted at the beginning of the register.

| Appearance of Buffer Index | | | | | | | |
|---|---|---|---|---|---|---|---|
| B(k) = | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | .... | 0.00 |
| **Appearance of Buffer State** | | | | | | | |
| X(k) = | 3.50 | 4.25 | 5.00 | 0.00 | 0.00 | .... | 0.00 |

FIGURE III-6

ILLUSTRATION OF THREE DATA POINTS
ON THE BUFFER SIMULATOR

3. Reliability

All reliability models are assumed to be exponential such that in any time step ($\tau$), the probability of a failure is:

$$P(f) = \int_0^{\tau} \frac{\exp\left(- \frac{ct}{MTBF}\right)}{MTBF} \, dt$$

where

| | | |
|---|---|---|
| P(f) | = | the probability of failure in time step $\tau$ |
| MTBF | = | the mean time between failures (in hours) |
| t | = | time in seconds |
| c | = | time conversion factor. |

In a like manner, maintenance time was assumed to be random with the probability of recovery:

$$P(r) = \int_0^{\tau} \frac{\exp\left(- \frac{ct}{MTTR}\right)}{MTTR} \, dt$$

where the new variables are

| | | |
|---|---|---|
| P(r) | = | the probability that the element is repaired in time step $\tau$ |
| MTTR | = | mean time to repair the element (in minutes). |

Descriptions of seven distinct system element models and the earth model were presented in this section. A typical model was seen to involve around 50 states, 10 input variables, and 10 output variables. Since the network configuration shown in Figures II-1 and II-2 contains approximately 30 elements, the simulator is a greatly simplified representation of the physical network. However, the simulator is considered sufficiently complete in the major elements to determine several interesting properties and statistics of the actual network. These are presented in the next section; the simulation results and analyses.

# SECTION IV
# RESULTS AND ANALYSIS

In this section we present the simulation record. Samples to validate the simulator and production runs are shown along with results from these runs and several analyses of the results.

## A. SIMULATION RECORD

A total of 25 different simulations were run. Their purpose and conditions are summarized in Table IV-1. They fall into validation integration and production type runs. Validation of the separate facility subprograms (REMOTE, COMNET, and CENTER) were completed early. However, problems arose during the integration which caused delays. Once these were solved, the production runs yielded the results to be presented.

## B. VALIDATION

All computer programs were reworked until an acceptable level of validity was achieved. Our object was to establish that the models are adequately representative of a subsystem.

In most cases deterministic forms of output were studied, such as the printout by time of all states of a model. Samples of this approach are provided in this section. In addition to these, statistical measures contained in the results section indicate reasonable validity of the simulator.

### 1. Earth Model

Figure IV-1 is a map showing the events generated by the earth model. As can be seen by comparison with actual seismicity maps, the earth

TABLE IV-1

SIMULATION RECORD

| Program | Purpose | Result |
|---|---|---|
| 1. COMNET | Validation | Valid |
| 2. EARTH | Validation | Valid |
| 3. SDP | Validation | Valid |
| 4. CENTER | Validation | Valid |
| 5. REMOTE & COMNET | Integration | Abort-too slow |
| 6. COMNET | Production | ok |
| Parameter Settings: | | |
| a. Block size, bits | | 480 |
| b. DB rate, no. per day | | 100, 300, and 500 |
| c. WFR rate, no. per day | | 30, 40, and 50 |
| 7. REMOTE & CENTER | Integration | Revise CENTER |
| 8. REMOTE & CENTER | Validation | Valid |
| 9. REMOTE & CENTER | Production | ok |
| Parameter Settings: | | |
| a. Number of regions | | 1 and 100 |
| b. False alarm rate, no. per hour | | 0.5 and 2.0 |
| c. Number of bulletins for assocation | | 4 |
| d. Error ellipse, No. of standard deviations | | 2, 4, 5, and 6 |
| Alternatives: | | Three large arrays |

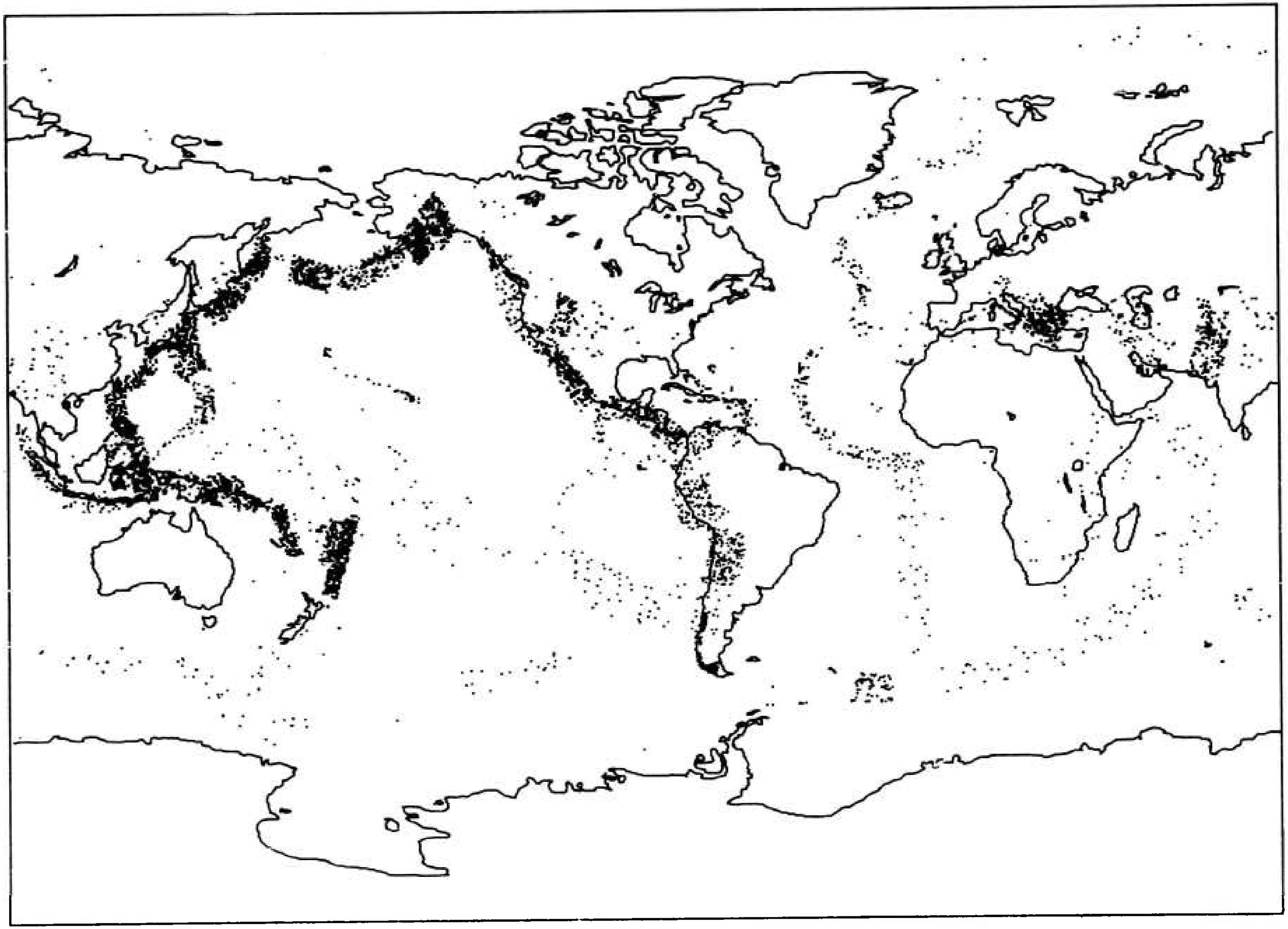


FIGURE IV-1

EARTH MODEL SEISMICITY MAP SHOWING 5000 SIMULATED EARTHQUAKE EPICENTERS model generates representative event distributions over 100 regions. The time and magnitude distribution of events is indicated in later sections. Table IV-2 provides a sample of the earth model output sequence.

2. Remote Facility

The station detection processor response to input noise and to the earth model input event sequence is shown by the simulated detection bulletin output in Table IV-3. We see that the DB output sequence contains all of the information expected on an actual bulletin to supply information to later processors and additional information for evaluation purposes as discussed in subsection III-C. The statistical validity of the DB output is indicated in subsequent sections regarding the remote facility, central facility, and network capability results.

3. Communications

Figure IV-2 is a sample of the Remote Communication Processor (RCP) state output by time. In this sample, the RCP received a status request (RQBS) from the CCP (via ICC) at time 30.60 seconds. The RCP responded with the status-ready to send or receive (STRS) signal. Then, after a delay of about four seconds the RCP received an exchange command (XCHR). In response, RCP sent the signal; acknowledge with information (ACWI) and then began transmission of DB number 15 at time 34.65 seconds.

To complete the story, the transmission was finished at time 42.00 seconds. The DB was removed from the RCP DB queue and it appeared on the CCP DB queue at 43.80 seconds.

Similar printouts are available for the CCP and for all modes of operation of the communications facility models.

TABLE IV-2

EARTH MODEL OUTPUT SAMPLE

| Event Time | | | | Event Number | Region Number | Latitude Degrees | Longitude Degrees | Depth Kilometers | Magnitude $m_b$ | Corner Period Seconds | Delay of the Maximum Peak | Average Events Per Day |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Hours | Minutes | Seconds | | | | | | | | | |
| 0 | 0 | 23 | 37.5 | 1 | 81 | -20.3 | -178.4 | 768.3 | 4.0 | 0.158 | 0.60 | 30.5 |
| 0 | 0 | 24 | 45.8 | 2 | 81 | -19.0 | -179.2 | 352.1 | 4.6 | 0.543 | 9.86 | 27.9 |
| 0 | 1 | 27 | 30.6 | 3 | 37 | 20.9 | -109.2 | 17.7 | 4.4 | 0.450 | 0.71 | 24.1 |
| 0 | 4 | 32 | 20.2 | 4 | 76 | -12.1 | 166.8 | 126.4 | 4.0 | 0.221 | 0.55 | 21.9 |
| 0 | 4 | 54 | 48.7 | 5 | 27 | -36.3 | - 66.9 | 122.8 | 5.2 | 1.603 | 13.36 | 24.8 |
| 0 | 5 | 33 | 38.1 | 6 | 23 | -59.8 | - 26.5 | 28.5 | 5.1 | 1.505 | 4.51 | 28.4 |
| 0 | 6 | 1 | 28.6 | 7 | 62 | 16.5 | 120.9 | 548.1 | 4.3 | 0.272 | 1.26 | 33.4 |
| 0 | 6 | 40 | 8.9 | 8 | 74 | - 2.4 | 150.2 | 348.6 | 4.1 | 0.228 | 2.04 | 32.4 |
| 0 | 8 | 11 | 0.6 | 9 | 32 | -23.2 | -113.6 | 58.6 | 4.1 | 0.242 | 1.65 | 31.3 |
| 0 | 8 | 36 | 52.8 | 10 | 42 | 42.5 | -129.5 | 15.2 | 4.6 | 0.671 | 0.83 | 29.4 |
| 0 | 9 | 24 | 11.9 | 11 | 25 | 37.1 | 68.2 | 48.5 | 4.1 | 0.266 | 8.75 | 28.2 |
| 0 | 10 | 1 | 45.8 | 12 | 16 | 42.9 | 22.6 | 76.1 | 4.8 | 0.850 | 0.50 | 24.1 |
| 0 | 10 | 48 | 48.9 | 13 | 59 | 24.1 | 141.8 | 69.4 | 5.2 | 1.509 | 1.36 | 23.2 |
| 0 | 18 | 41 | 18.9 | 14 | 56 | 43.1 | 141.2 | 81.1 | 4.4 | 0.447 | 4.37 | 20.1 |
| 0 | 20 | 44 | 25.7 | 15 | 74 | - 6.7 | 151.5 | 40.6 | 4.2 | 0.320 | 4.92 | 18.5 |
| 0 | 21 | 8 | 31.3 | 16 | 20 | 44.1 | 47.3 | 26.1 | 4.0 | 0.248 | 1.22 | 19.1 |
| 0 | 22 | 12 | 56.0 | 17 | 65 | - 6.8 | 116.4 | 96.5 | 5.5 | 2.862 | 0.72 | 18.5 |
| 0 | 22 | 30 | 32.2 | 18 | 65 | -11.6 | 119.7 | 21.0 | 4.1 | 0.268 | 3.63 | 16.0 |
| 1 | 1 | 9 | 15.5 | 19 | 29 | - 4.9 | - 79.1 | 36.9 | 4.8 | 0.953 | 1.50 | 17.3 |
| 1 | 1 | 43 | 43.8 | 20 | 63 | - 2.8 | 126.6 | 207.8 | 4.6 | 0.525 | 3.65 | 19.0 |
| 1 | 2 | 0 | 14.6 | 21 | 72 | - 4.1 | 128.2 | 109.9 | 4.4 | 0.400 | 0.89 | 21.2 |
| 1 | 2 | 12 | 6.9 | 22 | 46 | 59.8 | -157.3 | 292.8 | 4.5 | 0.450 | 3.04 | 18.7 |
| 1 | 2 | 37 | 49.6 | 23 | 48 | 52.6 | -169.8 | 215.0 | 4.1 | 0.227 | 3.98 | 18.9 |
| 1 | 3 | 2 | 23.7 | 24 | 80 | -18.3 | -173.9 | 338.9 | 4.3 | 0.296 | 0.50 | 17.4 |
| 1 | 3 | 47 | 33.6 | 25 | 48 | 54.4 | -160.5 | 4.4 | 5.0 | 1.494 | 3.70 | 17.3 |
| 1 | 4 | 18 | 22.7 | 26 | 35 | 18.0 | - 90.2 | 52.6 | 4.5 | 0.509 | 2.41 | 17.7 |
| 1 | 7 | 59 | 18.0 | 27 | 30 | - 9.1 | -106.9 | 18.7 | 5.6 | 3.539 | 0.50 | 15.8 |
| 1 | 8 | 56 | 25.8 | 28 | 46 | 54.6 | -154.0 | 800.0 | 4.5 | 0.322 | 0.50 | 18.8 |
| 1 | 9 | 18 | 34.8 | 29 | 66 | 3.2 | 98.0 | 36.5 | 4.5 | 0.503 | 11.29 | 20.6 |
| 1 | 10 | 34 | 36.9 | 30 | 35 | 14.1 | - 88.8 | 296.6 | 5.0 | 1.083 | 0.60 | 20.9 |

TABLE IV-3

STATION DETECTION PROCESSOR OUTPUT SAMPLE
(PAGE 1 OF 2)

| Bulletin Number | Time Slice 120 Sec. Duration | Station Number | Event Number | Interfering Event Number | Phase Number | Threshold Status | Detection Diagnostic | Time Error Diagnostic | Arrival Time, Sec. from Column 2 | Detector Z Statistic $m_b$ | Ray S. D. | Azimuth S. D. | Azimuth Degrees | Ray Sec. per Meter | Period Seconds | Threshold $m_b$ | Time Error | Azimuth Error | Ray Error |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 19 | 20 | 2 | 0 | 4 | 2 | 12 | 3 | -131.7 | 6.9 | 1.0 | 5.5 | 143.1 | 9.1 | 0.66 | 4.5 | -119.1 | 6.6 | 0.4 |
| 2 | 19 | 21 | 1 | 0 | 1 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 3 | 19 | 22 | 2 | 0 | 1 | 4 | 4 | 1 | -60.0 | 5.2 | 1.1 | 8.2 | 87.2 | 7.5 | 0.64 | 4.5 | 100.8 | -6.9 | 0.6 |
| 4 | 19 | 24 | 2 | 0 | 1 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 5 | 19 | 25 | 2 | 0 | 1 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.18 | 4.5 | 0.0 | 0.0 | 0.0 |
| 6 | 20 | 3 | 2 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.47 | 4.5 | 0.0 | 0.0 | 0.0 |
| 7 | 20 | 4 | 2 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 8 | 20 | 6 | 2 | 0 | 2 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 9 | 20 | 7 | 1 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 10 | 20 | 8 | 2 | 0 | 4 | 2 | 2 | 6 | 33.8 | 7.0 | 0.8 | 5.2 | 107.3 | 8.2 | 0.58 | 4.5 | -0.1 | -3.3 | 0.3 |
| 11 | 20 | 9 | 2 | 0 | 1 | 4 | 4 | 1 | -60.0 | 6.1 | 0.2 | 0.9 | 16.2 | 10.5 | 0.70 | 4.8 | 357.5 | 1.4 | -0.1 |
| 12 | 20 | 15 | 2 | 0 | 2 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 13 | 20 | 17 | 2 | 2 | 3 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.8 | 0.0 | 0.0 | 0.0 |
| 14 | 20 | 21 | 2 | 0 | 1 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 15 | 20 | 23 | 2 | 0 | 1 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.8 | 0.0 | 0.0 | 0.0 |
| 16 | 20 | 24 | 1 | 0 | 3 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 17 | 20 | 25 | 1 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.18 | 4.5 | 0.0 | 0.0 | 0.0 |
| 18 | 21 | 1 | 1 | 0 | 1 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.25 | 4.5 | 0.0 | 0.0 | 0.0 |
| 19 | 21 | 6 | 1 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 20 | 21 | 7 | 2 | 0 | 4 | 3 | 3 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 21 | 21 | 9 | 2 | 0 | 1 | 4 | 4 | 1 | -60.0 | 5.8 | 0.2 | 1.0 | 16.6 | 10.6 | 0.70 | 4.8 | 477.5 | 1.9 | -0.1 |
| 22 | 21 | 11 | 1 | 0 | 1 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 23 | 21 | 13 | 1 | 0 | 1 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 24 | 21 | 14 | 1 | 0 | 3 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.16 | 4.5 | 0.0 | 0.0 | 0.0 |
| 25 | 21 | 15 | 1 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |

TABLE IV-3

STATION DETECTION PROCESSOR OUTPUT SAMPLE
(PAGE 2 OF 2)

| Bulletin Number | Time Slice 120 Sec. Duration | Station Number | Event Number | Inter-fering Event Number | Phase Number | Thresh-old Status | Detec-tion Diag-nostic | Time Error Diag-nostic | Arrival Time, Sec. from Column 2 | Detec-tor Z Statis-tic $m_b$ | Ray S. D. | Azimuth S. D. | Azimuth Degrees | Ray Sec. per Meter | Period Seconds | Thresh-old $m_b$ | Time Error | Azimuth Error | Ray Error |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 21 | 17 | 2 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.8 | 0.0 | 0.0 | 0.0 |
| 27 | 21 | 19 | 1 | 0 | 3 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 28 | 21 | 21 | 1 | 0 | 3 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 29 | 21 | 23 | 1 | 0 | 3 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.8 | 0.0 | 0.0 | 0.0 |
| 30 | 21 | 24 | 2 | 0 | 3 | 2 | 2 | 2 | 59.5 | 7.7 | 0.7 | 15.1 | 292.1 | 2.5 | 0.57 | 4.5 | 9.4 | 27.6 | 0.0 |
| 31 | 21 | 25 | 2 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.18 | 4.5 | 0.0 | 0.0 | 0.0 |
| 32 | 22 | 1 | 1 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.25 | 4.5 | 0.0 | 0.0 | 0.0 |
| 33 | 22 | 6 | 2 | 2 | 4 | 2 | 2 | 6 | 29.1 | 5.2 | 1.0 | 8.0 | 242.1 | 6.4 | 0.61 | 4.5 | 0.0 | 6.2 | -0.4 |
| 34 | 22 | 9 | 2 | 0 | 1 | 4 | 4 | 1 | -60.0 | 5.9 | 0.2 | 1.0 | 16.1 | 10.7 | 0.70 | 4.8 | 597.5 | 1.4 | 0.1 |
| 35 | 22 | 11 | 2 | 0 | 1 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 36 | 22 | 13 | 2 | 0 | 1 | 2 | 2 | 2 | 6.1 | 9.0 | 0.5 | 9.1 | 53.5 | 2.8 | 0.49 | 4.5 | 9.9 | -2.4 | -0.5 |
| 37 | 22 | 14 | 1 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.16 | 4.5 | 0.0 | 0.0 | 0.0 |
| 38 | 22 | 15 | 2 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 39 | 22 | 19 | 1 | 0 | 1 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 40 | 22 | 21 | 1 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 41 | 22 | 23 | 2 | 0 | 3 | 3 | 3 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.8 | 0.0 | 0.0 | 0.0 |
| 42 | 22 | 24 | 2 | 0 | 4 | 2 | 2 | 6 | -24.3 | 5.7 | 1.0 | 7.4 | 278.7 | 6.8 | 0.63 | 4.5 | -0.1 | 14.3 | -0.3 |
| 43 | 23 | 1 | 2 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.25 | 4.5 | 0.0 | 0.0 | 0.0 |
| 44 | 23 | 11 | 2 | 0 | 1 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 45 | 23 | 13 | 2 | 0 | 1 | 2 | 2 | 6 | -124.0 | 9.0 | 0.5 | 9.1 | 53.5 | 2.8 | 0.49 | 4.5 | -0.3 | -2.4 | -0.5 |
| 46 | 23 | 14 | 2 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.16 | 4.5 | 0.0 | 0.0 | 0.0 |
| 47 | 23 | 19 | 2 | 0 | 1 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 48 | 23 | 21 | 2 | 0 | 4 | 0 | 6 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 4.5 | 0.0 | 0.0 | 0.0 |
| 49 | 23 | 23 | 2 | 0 | 4 | 2 | 2 | 6 | 16.2 | 6.3 | 0.2 | 1.5 | 14.3 | 5.9 | 0.66 | 4.8 | -0.0 | 0.2 | -0.3 |
| 50 | 24 | 9 | 2 | 0 | 1 | 4 | 4 | 1 | -60.0 | 4.9 | 0.3 | 1.2 | 16.8 | 10.5 | 0.70 | 4.8 | 837.5 | 2.1 | -0.1 |

## FIGURE IV-2

## COMMUNICATION VALIDATION SAMPLE
## (PAGE 1 OF 2)

| ICC INPUT TO RCP | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| TIME | NAFC | XCUR | ROBS | RSET | FLAG | PACK | WFR | ERR |
| 30.15 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 30.30 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 30.45 | 0. | 0. | 1. | 0. | 0 | 0. | 0. | 0. |
| 30.60 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 30.75 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 30.90 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 31.05 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 31.20 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 31.35 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 31.50 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 31.65 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 31.80 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 31.95 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 32.10 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 32.25 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 32.40 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 32.55 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 32.70 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 32.85 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 33.00 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 33.15 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 33.30 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 33.45 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 33.60 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 33.75 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 33.90 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 34.05 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 34.20 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 34.35 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 34.50 | 0. | 0. | 0 | 0. | 1. | 0. | 0. | 0. |
| 34.65 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 34.80 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 34.95 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 35.10 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 35.25 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 35.40 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 35.55 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 35.70 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 35.85 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |
| 36.00 | 0. | 0. | 0 | 0. | 0 | 0. | 0. | 0. |

FIGURE IV-2

COMMUNICATION VALIDATION SAMPLE
(PAGE 2 OF 2)

| RCP RESPONSE | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| TIME | NAFC | ACWI | ACPT | STRS | STNN | DBOT | WFOT | FLAG |
| 30.15 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 30.30 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 30.45 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 30.60 | 0. | 0 | 0. | 1. | 0. | 0 | 0. | 0. |
| 30.75 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 30.90 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 31.05 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 31.20 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 31.35 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 31.50 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 31.65 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 31.80 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 31.95 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 32.10 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 32.25 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 32.40 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 32.55 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 32.70 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 32.85 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 33.00 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 33.15 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 33.30 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 33.45 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 33.60 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 33.75 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 33.90 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 34.05 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 34.20 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 34.35 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 34.50 | 0. | 0 | 0. | 0 | 0. | 0 | 0. | 0. |
| 34.65 | 0. | 1. | 0. | 0 | 0. | 15. | 0. | 0. |
| 34.80 | 0. | 0 | 0. | 0 | 0. | 15. | 0. | 0. |
| 34.95 | 0. | 0 | 0. | 0 | 0. | 15. | 0. | 0. |
| 35.10 | 0. | 0 | 0. | 0 | 0. | 15. | 0. | 0. |
| 35.25 | 0. | 0 | 0. | 0 | 0. | 15. | 0. | 0. |
| 35.40 | 0. | 0 | 0. | 0 | 0. | 15. | 0. | 0. |
| 35.55 | 0. | 0 | 0. | 0 | 0. | 15. | 0. | 0. |
| 35.70 | 0. | 0 | 0. | 0 | 0. | 15. | 0. | 0. |
| 35.85 | 0. | 0 | 0. | 0 | 0. | 15. | 0. | 0. |
| 36.00 | 0. | 0 | 0. | 0 | 0. | 15. | 0. | 0. |

### 4. Central Facility

In the central facility, validation concerned primarily the detection association processor. Table IV-4 gives a record of the location estimate error statistics after DAP processing. We see that the estimator is of low bias and the error standard deviation is reasonable. The large time standard deviation is due to approximate travel-time curves used in the simulator and because the estimates were depth constrained. Also, the association algorithm is implemented only approximately. Two approximations were that the error ellipse rotation was not considered and the procedure for selecting bulletins was simplified to take all available bulletins into the association rather than the best three or four. Therefore, the DAP output should be used for relative comparisons. For other purposes, such as capability estimation, somewhat large errors are permitted before the DAP is scored as having a wrong answer. The general validity, however is further documented by the results to be presented.

## C. REMOTE FACILITY

Since the communication facility program was separated from the remote facility simulation, capability statistics are primary results of the remote facility simulation. It should be noted that these differ from earlier capability estimates because the earth model presents to the detector a more difficult problem than is assumed in earlier analystic methods.

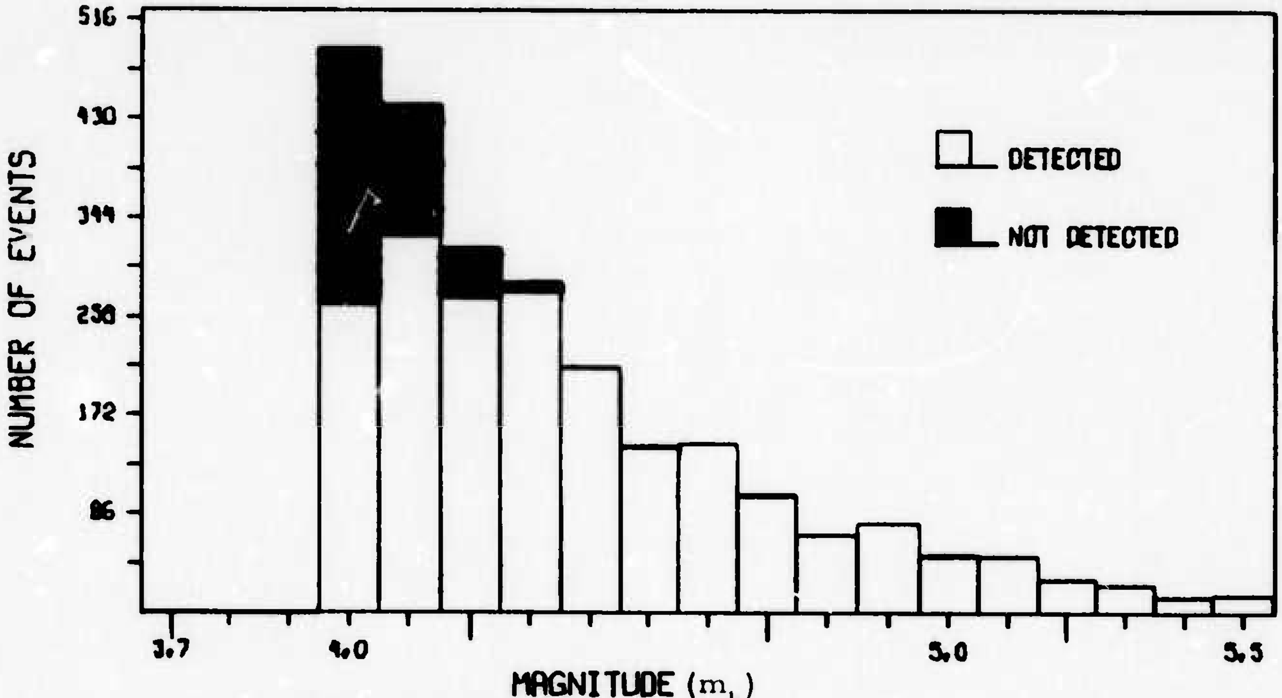
Figures IV-3 to IV-6 present histograms of the number of events by magnitude and detectability curves. The detectability curves are for one-or-more through four-or-more stations detecting an event.

These were developed by tabulating, from the detection bulletin output sequence from each station, the events detected by magnitude. This was done for the northern and southern hemisphere and for all regions. The detectability curves are for all regions simulated.

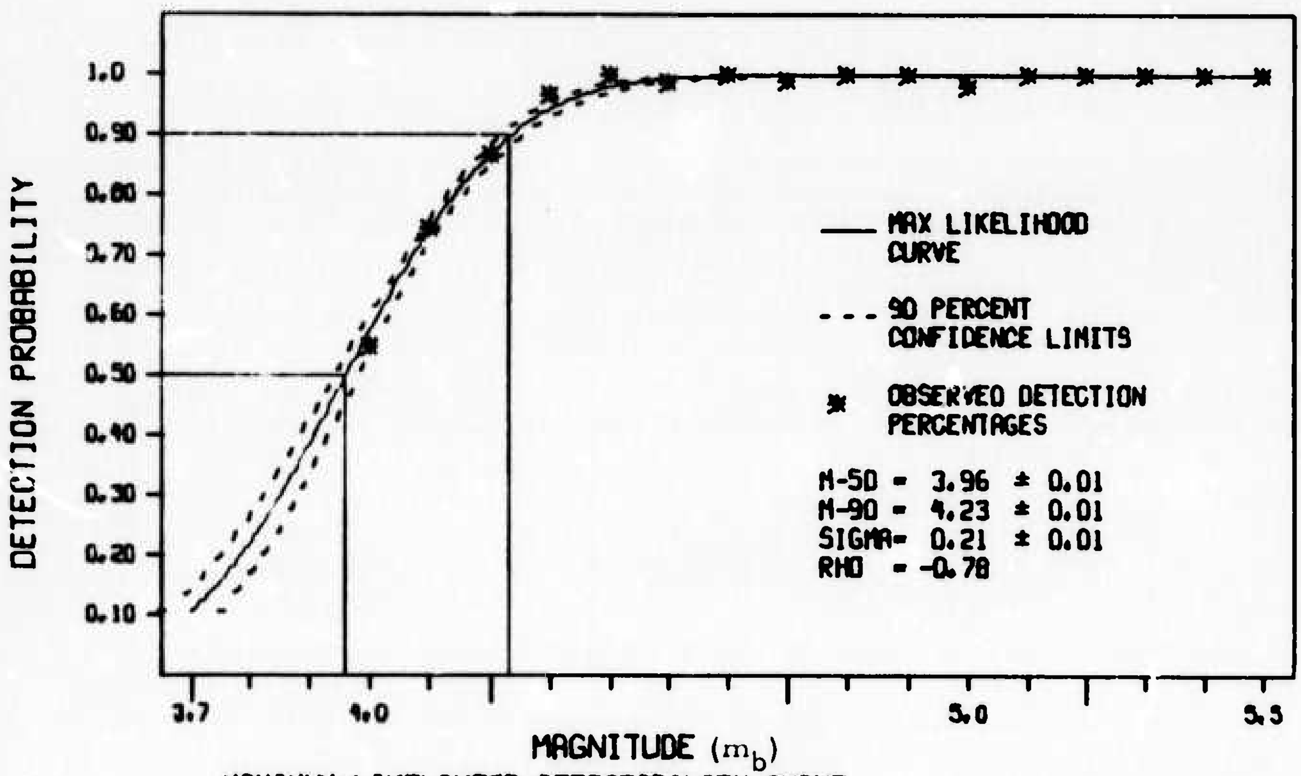
TABLE IV-4

CENTRAL FACILITY VALIDATION SAMPLE

| Simulated Number | Event Magnitude | Estimate Error | | |
|---|---|---|---|---|
| | | Time Seconds | Latitude Degrees | Longitude Degrees |
| 1 | 5.3 | -19.0 | 1.99 | -4.18 |
| 3 | 4.3 | - 2.1 | 1.35 | 1.14 |
| 7 | 4.4 | 0.1 | -0.51 | -0.09 |
| 9 | 4.5 | - 3.2 | 0.29 | 0.55 |
| 10 | 4.7 | 1.8 | -0.07 | -0.07 |
| 13 | 4.8 | 24.0 | -0.70 | 2.55 |
| 14 | 5.1 | - 5.9 | -0.31 | -0.22 |
| 15 | 5.1 | -22.7 | 13.40 | -7.49 |
| 16 | 4.9 | 3.6 | -0.58 | +0.35 |
| 17 | 4.7 | - 1.1 | 0.47 | -0.23 |
| 18 | 4.3 | 25.3 | -3.78 | 1.67 |
| 19 | 4.7 | - 0.2 | 0.16 | 2.30 |
| 23 | 6.3 | 8.0 | 0.37 | 0.04 |
| 24 | 4.5 | 2.6 | 0.24 | 0.01 |
| $\bar{x}$ | = | 0.716 | 0.225 | 0.175 |
| $\sigma$ | = | 9.43 | 0.752 | 1.60 |



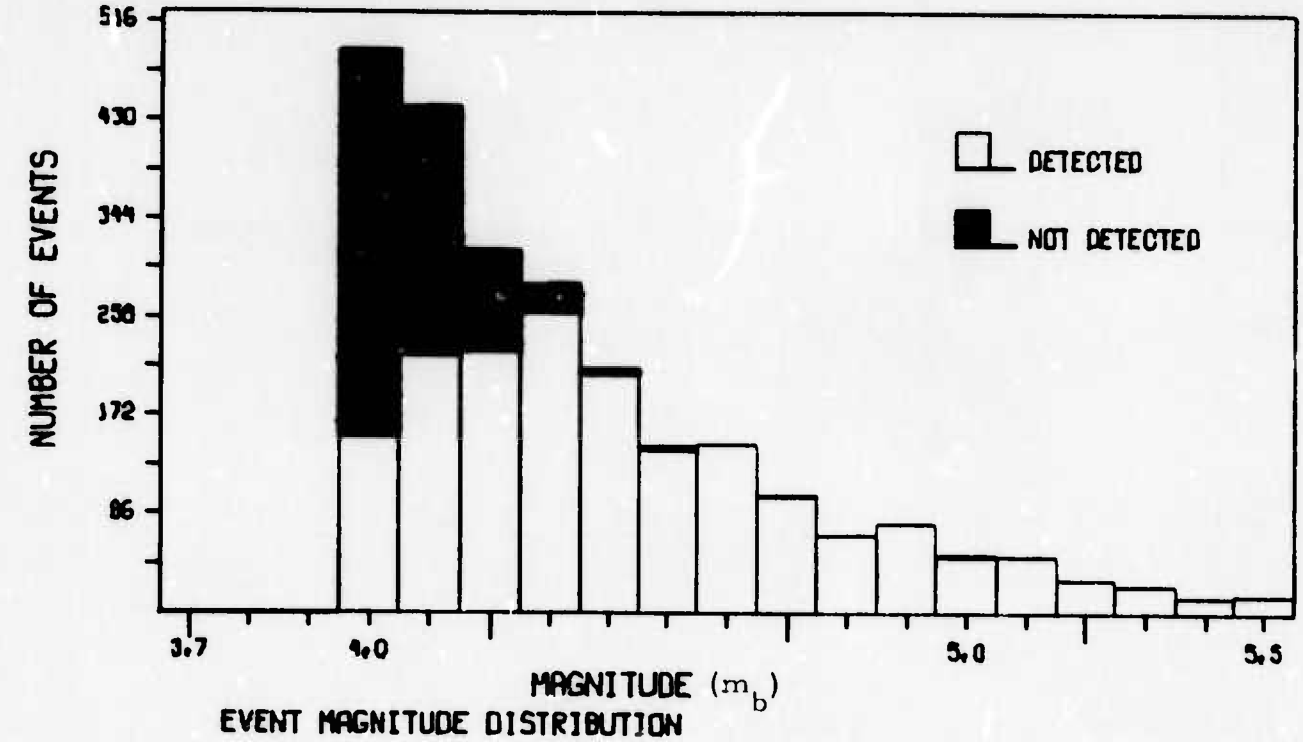

EVENT MAGNITUDE DISTRIBUTION



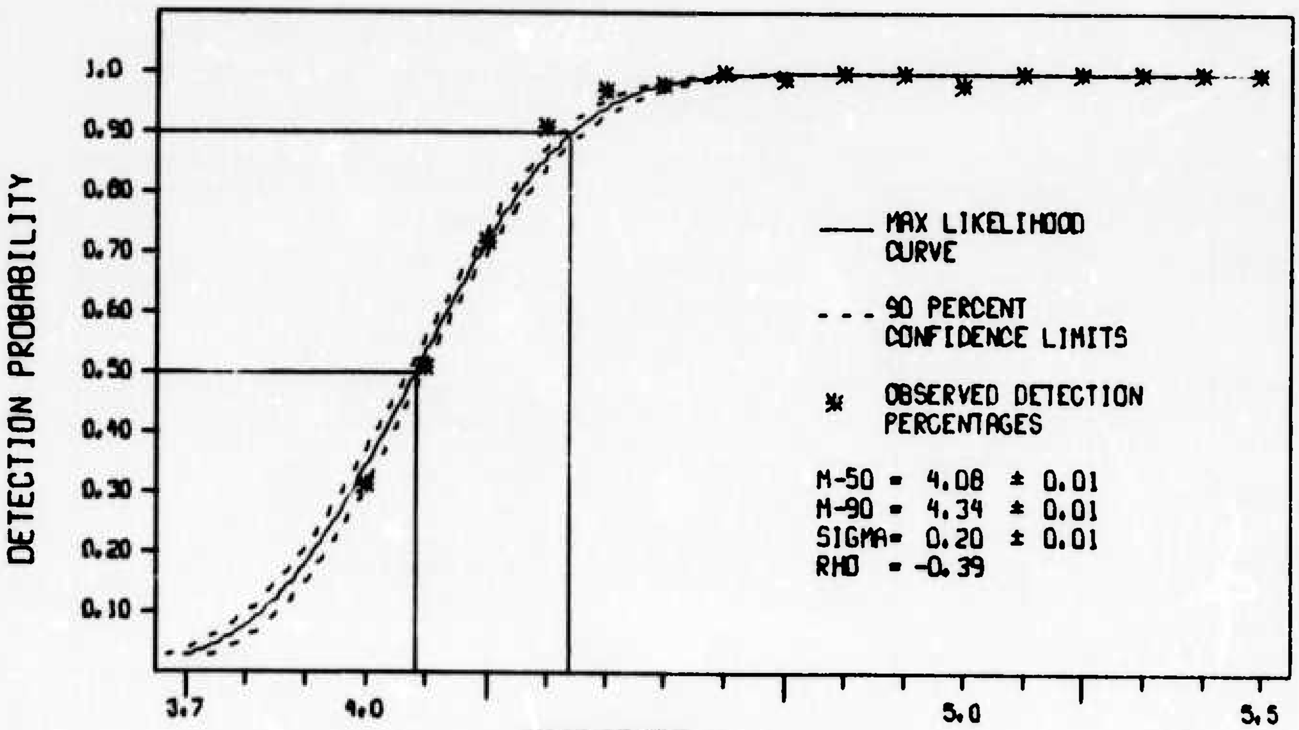

MAXIMUM LIKELIHOOD DETECTABILITY CURVE

FIGURE IV-3

STATIONS DETECTION CAPABILITY FOR ONE OR MORE STATIONS DETECTING



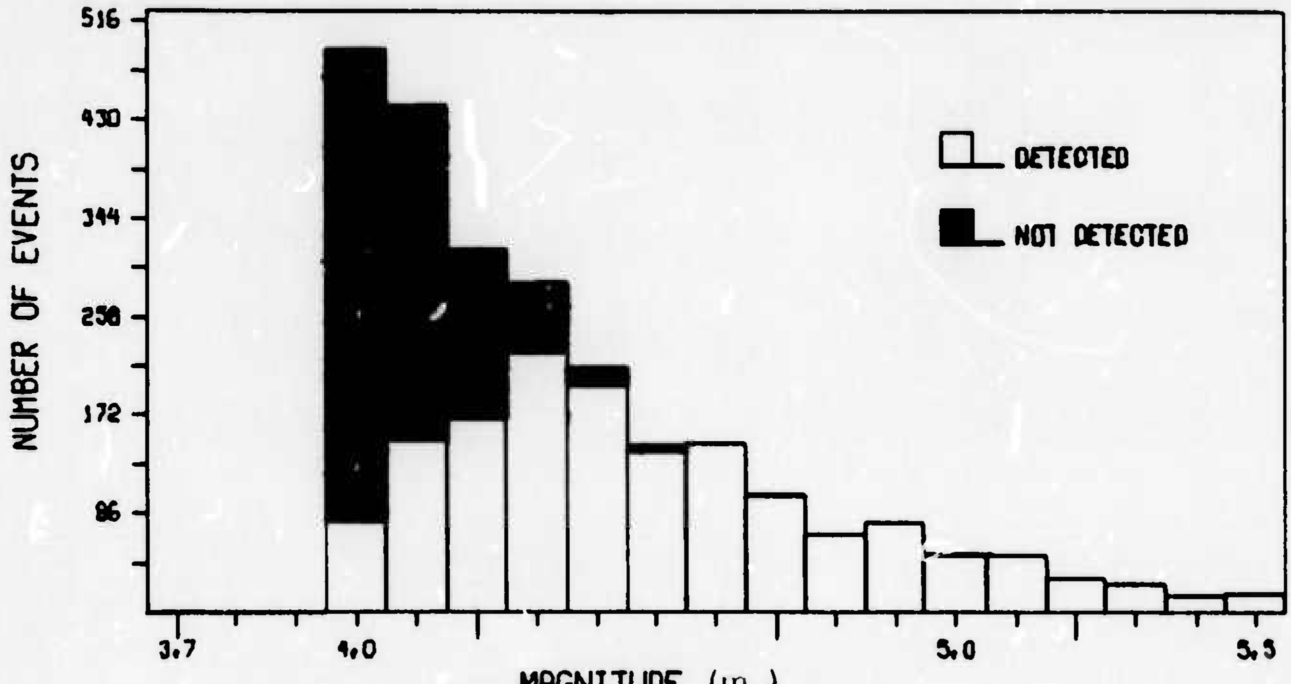
EVENT MAGNITUDE DISTRIBUTION



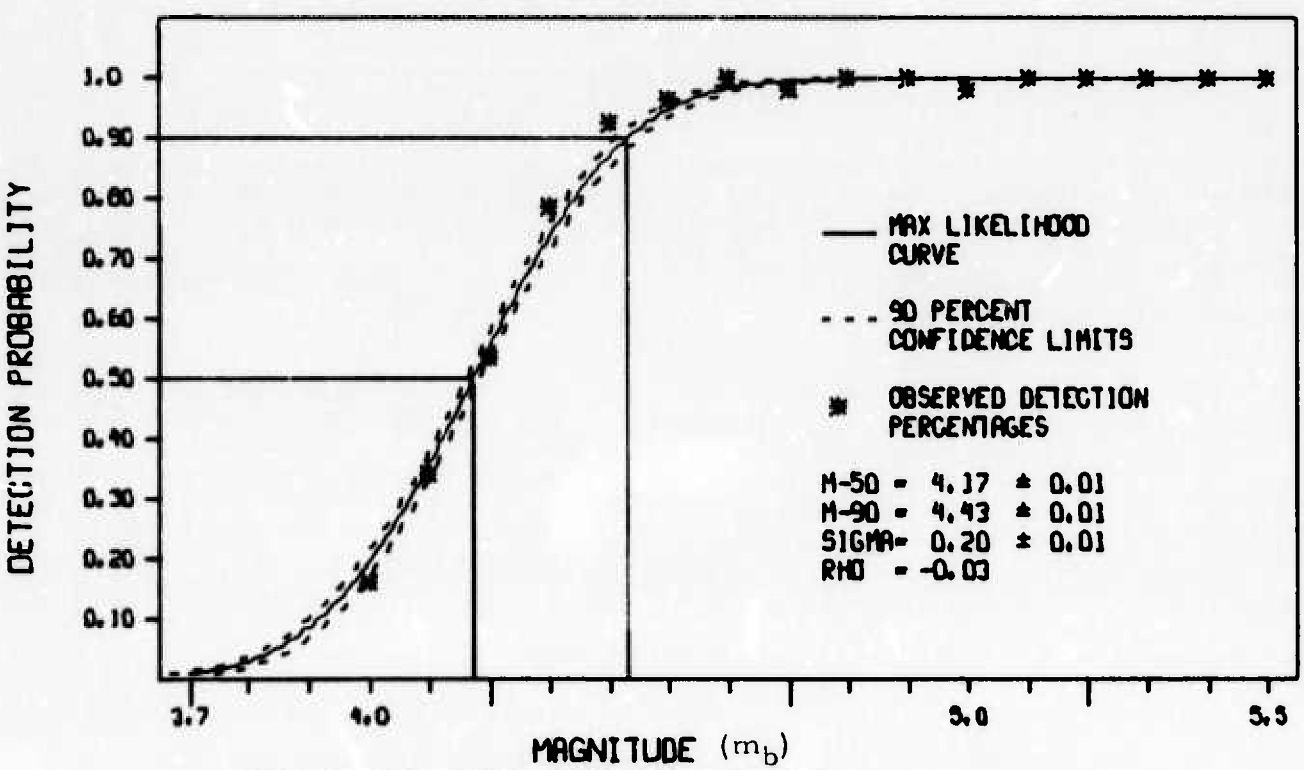
MAXIMUM LIKELIHOOD DETECTABILITY CURVE

FIGURE IV-4

STATIONS DETECTION CAPABILITY FOR TWO OR MORE STATIONS DETECTING



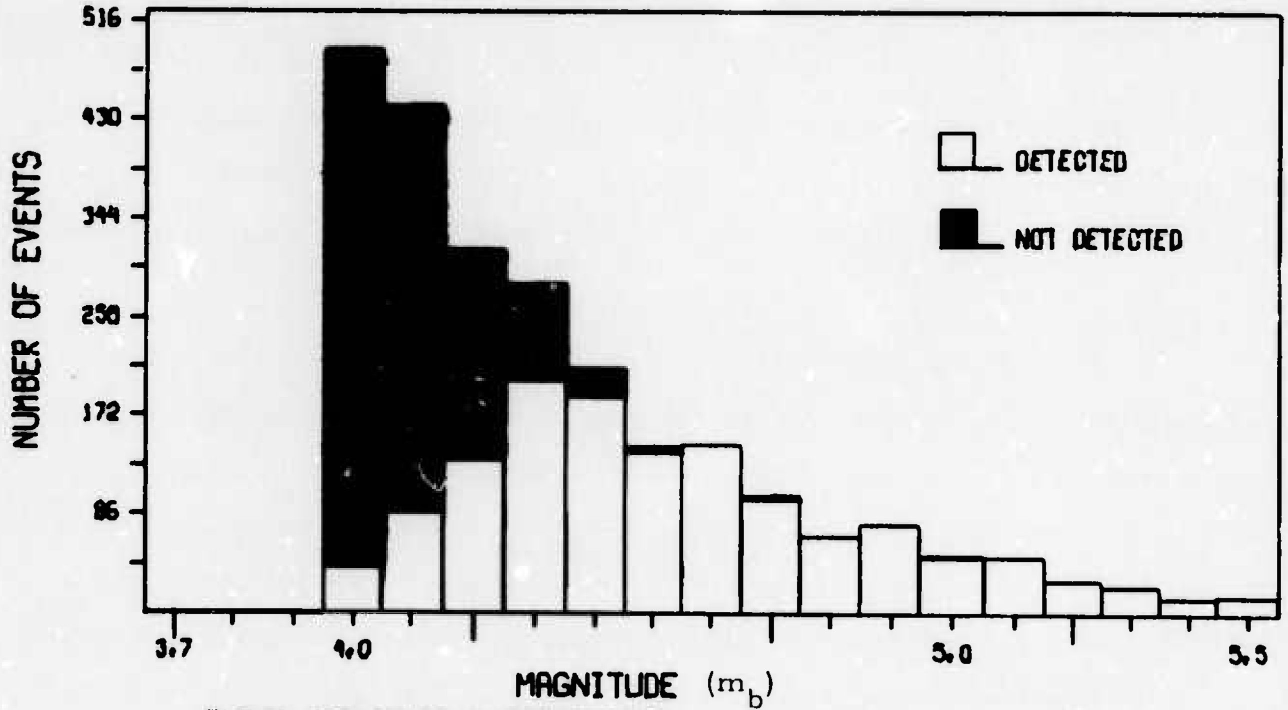

EVENT MAGNITUDE DISTRIBUTION



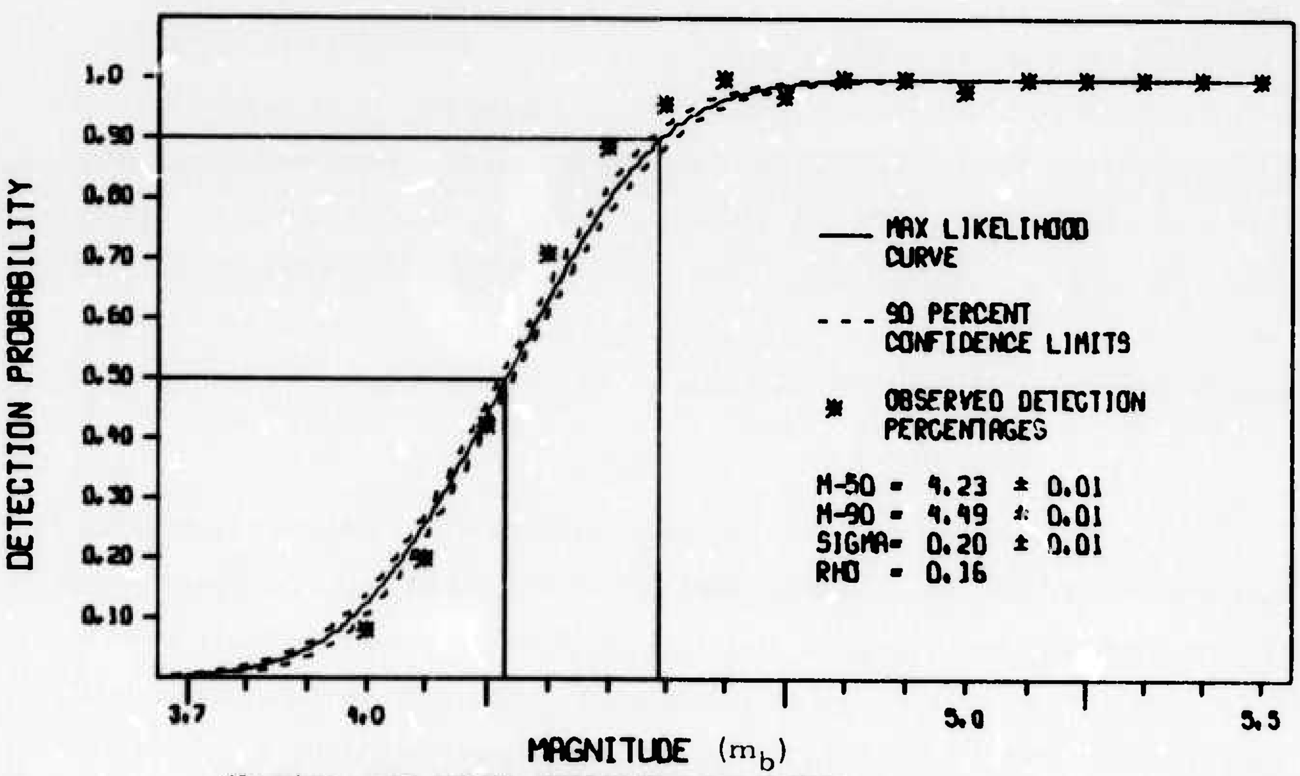

MAXIMUM LIKELIHOOD DETECTABILITY CURVE

FIGURE IV-5

STATIONS DETECTION CAPABILITY FOR THREE OR MORE STATIONS DETECTING




EVENT MAGNITUDE DISTRIBUTION




MAXIMUM LIKELIHOOD DETECTABILITY CURVE

FIGURE IV-6

STATIONS DETECTION CAPABILITY FOR FOUR OR MORE STATIONS DETECTING

The results represent the potential capability of the network. In particular the four-or-more stations curve is compared in subsection IV-F (Network Performance), with the simulated results for the network.

## D. COMMUNICATIONS

In the paragraphs to follow, communications results and their analyses are presented. As remarked earlier, the COMNET production runs are for the communications facility alone. To have inputs at the RCP and CCP, certain assumptions were made. First, it was assumed that a range of DB input rates generated from a binomial density are representative of the short-term arrival rates at the RCP. Second, it was assumed that a binomial probability of a bulletin generating or resulting in a waveform request was representative of the WFR arrival rate at the CCP and their correlation with previous DB's. Also, the WFR's were delayed five minutes before transmission to simulate the central facility delay. This appears to be too short of a delay - a better figure would be 15 minutes. The impact is to reduce the correlation between the number of DB's and WF's being handled at the same time. For example, in the simulation, during a swarm earlier DB's will tend to generate WF messages with nearly contemporary DB's rather than with later DB's as it should be. The following results are presented in terms of the performance measures reliability, utilization, queues, and delays.

### 1. Reliability

No communications system failures were observed in the 36 hours of simulation, but since the separate simulation trials were begun with the same random numbers, the simulated time for system reliability is only three hours. Therefore, we are unable to remark on the impact of reliability except to note that for the three failure modes identified (RCP, ICC, and CCP) from standard calculations (Figure IV-7) the observed failure rate would be

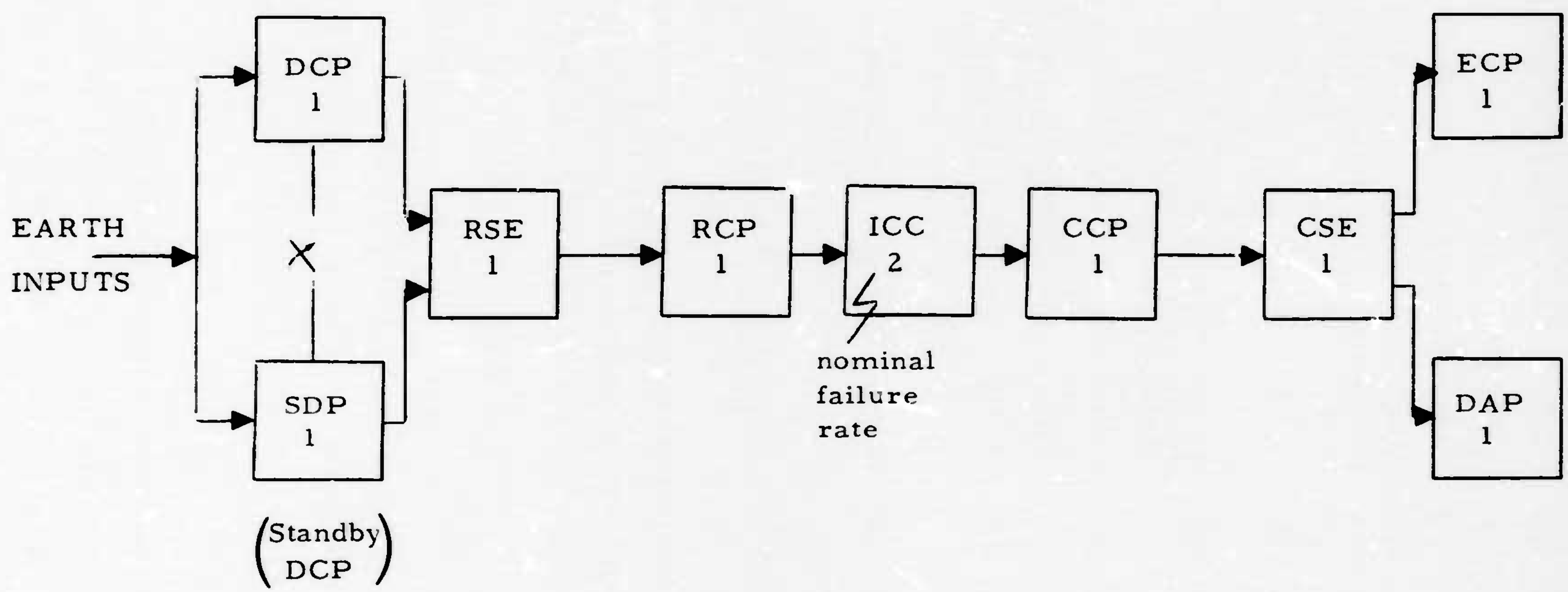



FIGURE IV-7

NETWORK FAILURE MODES SHOWING
NOMINAL FAILURE RATES PER YEAR

5.5 failures per year per station. Then for the network of 25 stations, 138 failures could be expected for this subsystem alone. Considering all of the other failure modes of the network, this could amount to a considerable bother at the central facility.

2. Utilization

Figure IV-8 is a time-series representation of the communications system utilization for the conditions shown. The two horizontal lines at the top of this figure are the computed effective capacities for the two types of error control procedures; stop-and-wait ARQ and continuous ARQ. The former method is the simulated method and the latter is not simulated but it is an alternative.

It seems evident that if this result is representative, then the continuous ARQ would add little to the communications system effectiveness or information rate. The capacity is increased by 0.8 percent while due to protocol the data rate demanded is far below the capacity ranging from 10 percent to around 80 percent. In addition, the cost of the continuous ARQ is about twice as much for software and requires a full duplex system or, for example, two 50 bps leased lines so that the operating cost would be about twice as high as that of the simulated alternative.

The varying demand apparent in this figure is the result of the central facility operating procedure and the observed capacity during transmission is due to the protocol so these two areas are indicated for improving the communications system effectiveness.

3. Queues

Time series for the six queue measurements are displayed in Figure IV-9. The series shown are the DB queue (DBQ), the WF message queue (WFQ) and the WFR queue (WFRQ) for both the RCP and the CCP.

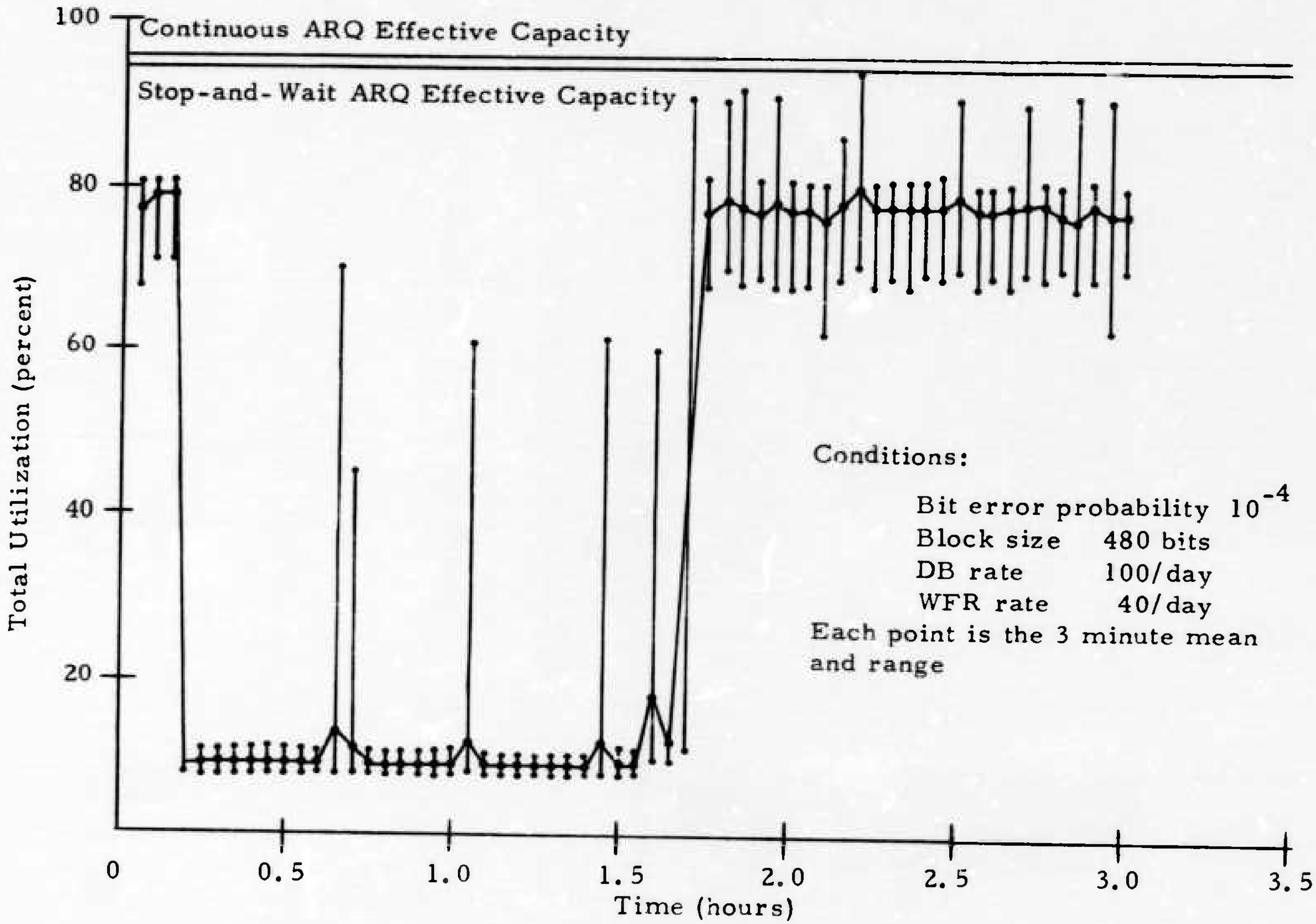



FIGURE IV-8

UTILIZATION TIME SERIES SHOWING EFFECTIVE CAPACITY AND MEAN TOTAL UTILIZATION

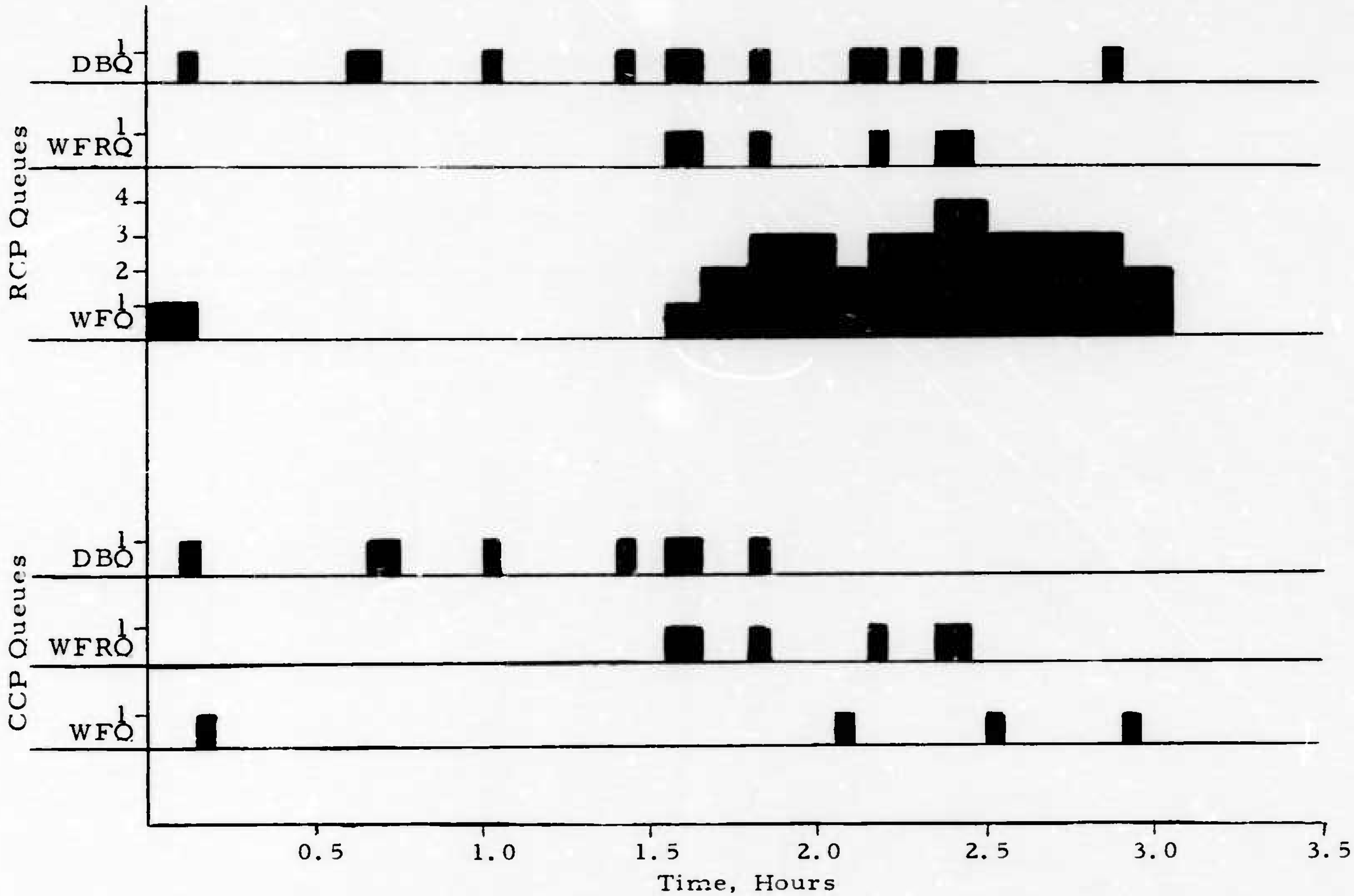



FIGURE IV-9

COMMUNICATIONS MESSAGE QUEUES TIME SERIES

From the figure, we see that all DBQ's were at most one in length and were retained less than six minutes. The same is seen to be true for WFQ's at both processors, and for the WFQ at the CCP. At the RCP, however, the WFQ reached four in length, and averaged around three for a period of about an hour and a half. We also note that during this period if the DB rate had been higher, build up of the DBQ would have occurred due to crosscorrelation with the WFQ. This result is indicated by the data in Table IV-5.

Table IV-5 summarizes the queue data for other DB and WFR rates. The table shows that at high detection rates, the DBQ did build up due to the crosscorrelation noted in the above paragraph. The maximum length was four bulletins, all cases of which occurred at the high detection rate. The WFQ reached four at several WFR rates with a mean and standard deviation of about 1.5 messages. In no case was the WFRQ a problem since it is going the other direction, i.e., from CCP to RCP.

The simulator uses fixed allocation of buffer space. Other alternatives are various dynamic allocation schemes. But at the RCP the only queue of consequence is the WFQ. So to what should we allocate the space when there are no WF's? Also, due to correlation, DB's often require space at the same time as the WF's. A WF requires about 8 k bits of memory while a DB requires 0.6 k bits. Even for 25 stations the core cost of fixed buffer allocation is probably less than the software development cost for dynamic buffering, not to mention the software maintenance cost, time, and personnel implications at the remote facility.

At the CCP, the simulation queue results are for just a single channel. Queues for the network depend on the CCP access method which has not been simulated. But the single channel results shown in Table IV-6 may be interpreted for the various access methods. The table shows that at the CCP, the maximum queue length for any message was one. The result is sensitive only to CSE failures and delays or to a channel failure.

TABLE IV-5

REMOTE COMMUNICATIONS PROCESSOR QUEUE STATISTICS

| Test Conditions* | | Detection Bulletins | | | Waveform Messages | | | Waveform Requests | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DB Rate No./Day | WFR Rate No./Day | Maximum | Mean | S. D. | Maximum | Mean | S. D. | Maximum | Mean | S. D. |
| 100 | 30 | 1 | 0.03 | 0.16 | 2 | 0.68 | 0.75 | 1 | 0.0 | 0.04 |
| 100 | 40 | 1 | 0.03 | 0.16 | 4 | 1.38 | 1.41 | 1 | 0.0 | 0.04 |
| 100 | 50 | 1 | 0.03 | 0.16 | 4 | 1.54 | 1.58 | 1 | 0.0 | 0.05 |
| 300 | 30 | 1 | 0.06 | 0.22 | 4 | 1.59 | 1.28 | 1 | 0.0 | 0.05 |
| 300 | 40 | 1 | 0.06 | 0.22 | 3 | 1.49 | 0.88 | 1 | 0.0 | 0.04 |
| 300 | 50 | 1 | 0.06 | 0.22 | 3 | 1.49 | 0.88 | 1 | 0.0 | 0.04 |
| 500 | 30 | 4 | 0.18 | 0.56 | 3 | 1.01 | 0.80 | 1 | 0.0 | 0.04 |
| 500 | 40 | 4 | 0.18 | 0.56 | 3 | 1.01 | 0.80 | 1 | 0.0 | 0.04 |
| 500 | 50 | 4 | 0.18 | 0.56 | 3 | 1.43 | 1.04 | 1 | 0.0 | 0.05 |

* Other Conditions

1. Block size 480 bits 2. Simulation time 4 hours 3. Bit error probability $10^{-4}$

TABLE IV-6

CENTRAL COMMUNICATIONS PROCESSOR QUEUE STATISTICS

| Test Conditions* | | Detection Bulletins | | | Waveform Messages | | | Waveform Requests | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DB Rate No. / Day | WFR Rate No. / Day | Maximum | Mean | S. D. | Maximum | Mean | S. D. | Maximum | Mean | S. D. |
| 100 | 30 | 1 | 0. 01 | 0. 06 | 1 | 0. 03 | 0. 18 | 1 | 0. 00 | 0. 04 |
| 100 | 40 | 1 | 0. 01 | 0. 07 | 1 | 0. 04 | 0. 18 | 1 | 0. 00 | 0. 05 |
| 100 | 50 | 1 | 0. 01 | 0. 06 | 1 | 0. 04 | 0. 19 | 1 | 0. 00 | 0. 04 |
| 300 | 30 | 1 | 0. 03 | 0. 13 | 1 | 0. 07 | 0. 26 | 1 | 0. 01 | 0. 06 |
| 300 | 40 | 1 | 0. 03 | 0. 14 | 1 | 0. 04 | 0. 19 | 1 | 0. 01 | 0. 06 |
| 300 | 50 | 1 | 0. 03 | 0. 14 | 1 | 0. 04 | 0. 19 | 1 | 0. 01 | 0. 06 |
| 500 | 30 | 1 | 0. 05 | 0. 17 | 1 | 0. 04 | 0. 19 | 1 | 0. 00 | 0. 06 |
| 500 | 40 | 1 | 0. 05 | 0. 17 | 1 | 0. 04 | 0. 19 | 1 | 0. 00 | 0. 06 |
| 500 | 50 | 1 | 0. 05 | 0. 17 | 1 | 0. 04 | 0. 19 | 1 | 0. 00 | 0. 05 |

*Other Conditions

1. Block size 480 bits   2. Simulation time 4 hours   3. Bit error probability $10^{-4}$

In general, the access method concerns the number of stations that can transmit in parallel and, if the number is less than 25, the ordering procedure; demand or interrupt, time division, or a procedure based on the RCP queue statuses. Without simulation we do not know but, because of the long send time for WF messages, perhaps 10 stations would like to send at the same time. The access method impacts the WF delay and the buffer allocation approach. Two methods appear to be indicated; a status based method or a packet based method.

The first method allows, say, five stations to have simultaneous access and provides storage for five WF messages or about 40 k bits. The second assigns to all stations memory for several packets and during protocol delays writes these to disk. An area may be necessary for re-sequencing the packets of completed messages so the core requirement is about 10 k bits; 8 k for the edit area and 2 k for 50 packet of 400 bits. Further simulation is required to determine the better method.

4. Delays

From the delay information of Figure IV-10 we see that the DB delay is between 30 and 150 seconds while the WF delays ranged from 30 to more than 60 minutes. This is the total delay or cumulative delay including 5 minutes at the central facility. Two factors are seen to contribute to the WF message delay; the DB rate since DB's have priority over WF's, and the correlation in WFR's that generated the WF messages. Slicing or interleaving of DB's and WF's in this figure is caused by the DB priority. The notch at time 2.5 hours in the WF cumulative age is due to WFR#3 being more recent than 1 and 2, which apparently were nearly simultaneous. The effects for different operating conditions are shown in Table IV-7.

This table shows several general results; the minimum time to send a DB is one half minute for all conditions, and the maximum time to send

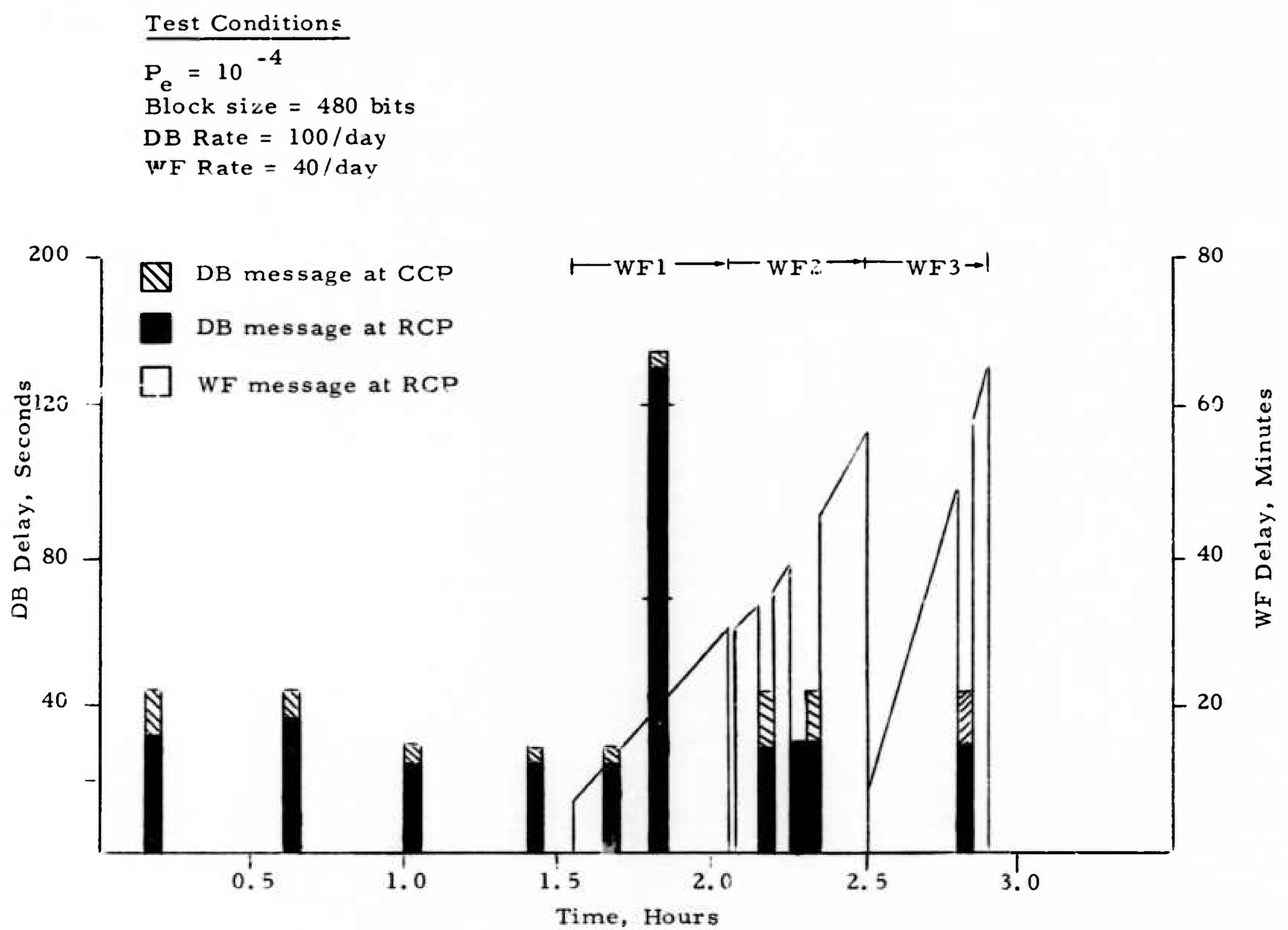



FIGURE IV-10

COMMUNICATIONS DETECTION BULLETIN AND WAVEFORM MESSAGE DELAY TIME SERIES

TABLE IV-7

COMMUNICATIONS FACILITY DELAY STATISTICS

| Test Conditions* | | Detection Bulletins | | Waveform Messages | | | | Waveform Requests | |
|---|---|---|---|---|---|---|---|---|---|
| DB Rate No. / Day | WFR Rate No. / Day | Minimum Minutes | Maximum Minutes | Minimum Minutes | Maximum Minutes | Mean Minutes | S. D. | Number Cases | Maximum Seconds |
| 100 | 30 | 0.495 | 2.23 | 30.92 | 57.64 | 40.6 | 12.1 | 3 | 15 |
| 100 | 40 | 0.495 | 2.23 | 31.17 | 66.55 | 41.5 | 28.0 | 3 | 15 |
| 100 | 50 | 0.495 | 2.23 | 31.17 | 78.42 | 55.8 | 19.3 | 3 | 15 |
| 300 | 30 | 0.495 | 0.99 | 27.46 | 59.20 | 42.3 | 13.9 | 5 | 15 |
| 300 | 40 | 0.495 | 0.75 | 31.42 | 59.19 | 35.7 | 28.4 | 5 | 15 |
| 300 | 50 | 0.495 | 0.75 | 30.91 | 59.90 | 42.7 | 9.8 | 5 | 15 |
| 500 | 30 | 0.495 | 5.94 | 34.39 | 60.86 | 50.7 | 11.7 | 3 | 15 |
| 500 | 40 | 0.495 | 5.94 | 29.48 | 60.86 | 49.1 | 13.6 | 3 | 15 |
| 500 | 50 | 0.495 | 5.94 | 34.39 | 60.86 | 50.8 | 11.7 | 3 | 15 |

*Other Conditions

1. Block size 480 bits  2. Simulated time 3 hours  3. Bit error probability $10^{-4}$

W.^R's is 15 seconds, for all conditions. The average cumulative delay for WF messages was about 45 minutes for all conditions. For modeling purposes a result is that the WF message 'service time' is about 30 minutes so that the delay for a message is this plus 30 minutes per messages on queue before it. Minor variations are caused by the DB rate and status of the communications system when it arrives.

The delay values shown are sensitive mainly to the CCP access method (subsection IV-B-2). The present assumption is that there are no access delays.

## E. CENTRAL FACILITY

Results and analyses from the central facility simulation are presented in this subsection. Included are reliability, utilization and queueing and processor performance data. Because the central facility simulation was separated from the communications facility, results for several of these topics are based on the system model rather than on computer runs. Also, due to the short simulation runs, the results are tentative as they involve significant uncertainty.

### 1. Reliability

No failures occurred during the tests which covered about three simulated days. However, for the input failure rates and simulated configuration, (subsection IV-D-1) approximately 138 station failures are expected to occur per year in the data path to the DAP and about 275 failures per year in the path to the event classification processor. This may lead to some difficulty in operating the system but is expected to have little effect in the network capability.

2. Utilization

In Table IV-8 is the simulator run time for the DAP and the time simulated. Since the DAP actually performs the processing, the time represents the run time for a finished algorithm. Several features are omitted though, so an order of magnitude estimate of the DAP utilization for the limited DAP algorithm being simulated is about 7 percent. This suggests that there is no queueing problem at the DAP and also that there is considerable time available for a more elaborate DAP. We will see that this elaboration may be necessary in order to fully utilize the other network elements.

3. Queues

Although no input queueing information was developed for the central facility, it is apparent that from the DAP utilization that no queues would develop except in the case of a failure of the DAP processor.

The output queue is expected to be two messages, at most, to about ten stations and these would be sent in within 15 seconds. Figure IV-11 shows the output waveform request time series by station. We note that two messages within 15 seconds is a conservative assumption on the output message queue.

The output time series of this figure is the arrival time series at the stations, therefore, this data can be used to develop a macro-model for the arrival time of messages at the stations.

4. DAP Capability

The output of the detection association processor is waveform request messages. These can be the desired seismic events, redundant messages related to the coda of events, or completely false messages. After large events, many redundant messages are sent. This can be seen in the WFR output time series in Figure IV-12. In this figure bars represent the

TABLE IV-8

DAP UTILIZATION DATA

| Hours Simulated | Run Time Minutes | Utilization Percent |
|---|---|---|
| 32.0 | 13.5 | 0.703 |
| 33.0 | 14.0 | 0.707 |
| 33.45 | 13.0 | 0.648 |
| | | $\overline{X} = 0.686$ |

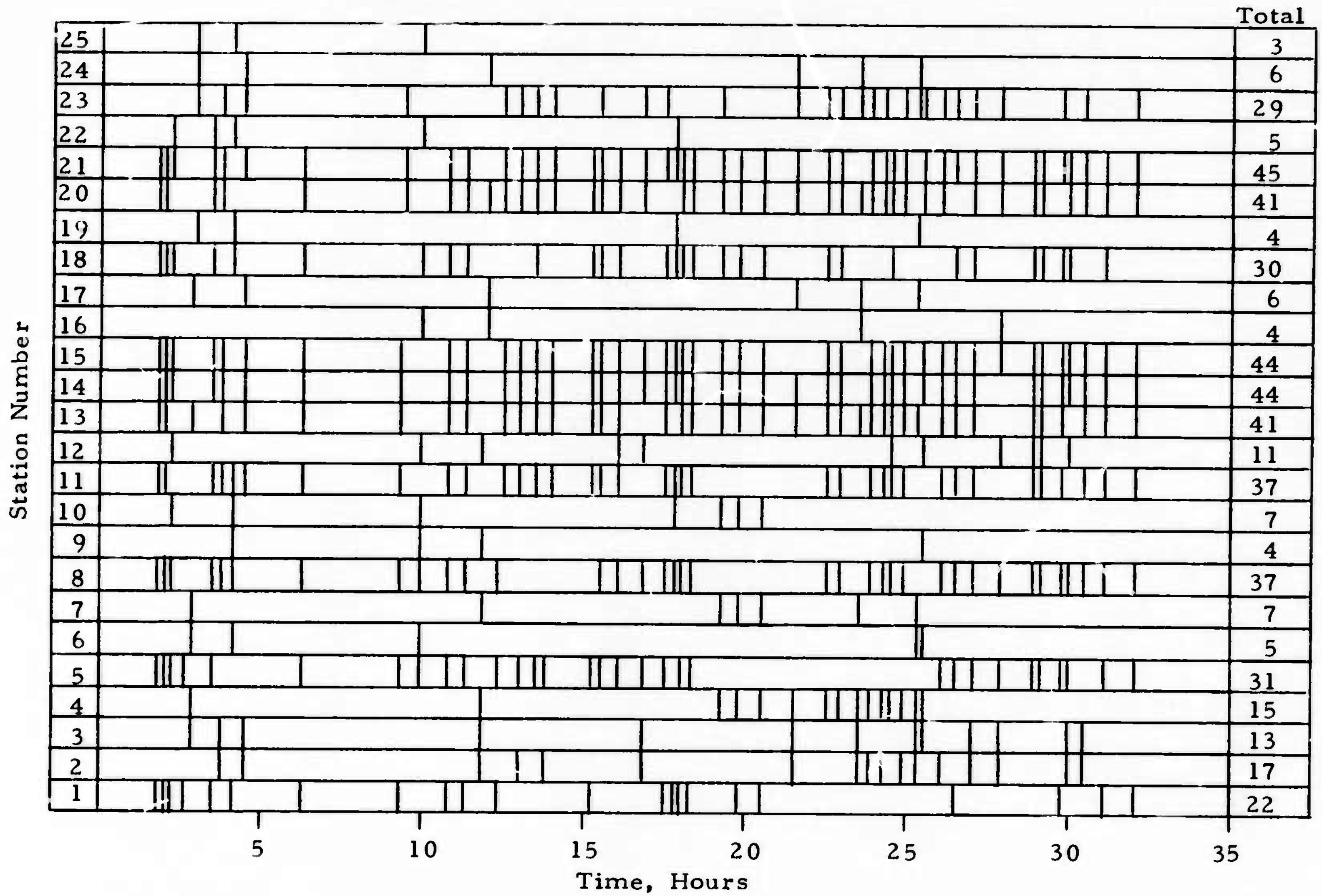



FIGURE IV-11

WAVEFORM REQUEST OUTPUT OF THE DAP WHEN ALL EVENTS ARE FROM ONE REGION

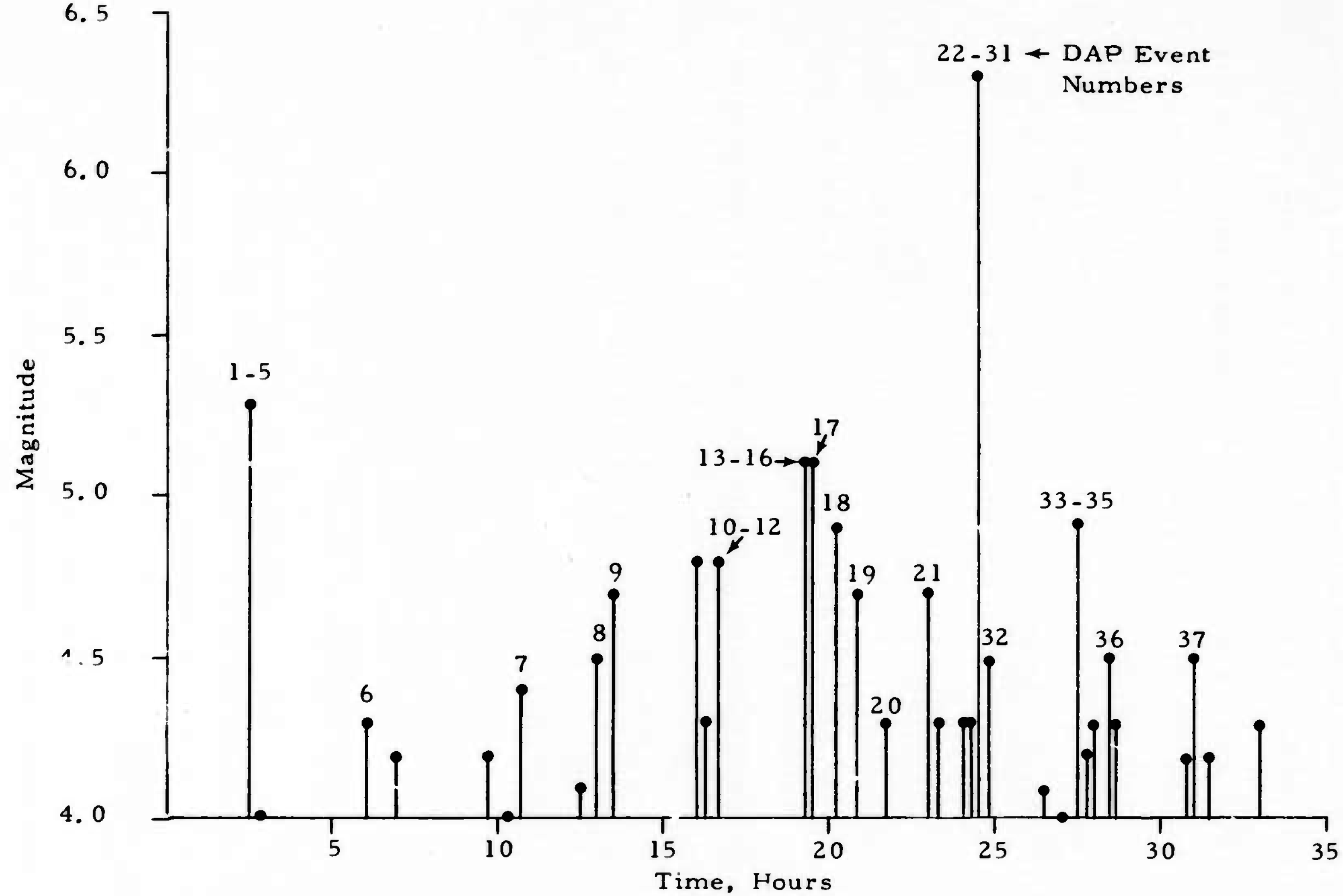



FIGURE IV-12

TIME PLOT OF ACTUAL EVENTS AND DAP EVENTS time of the output message and the magnitude of the actual event. The numbers at the top of the bars is the DAP event numbers associated with the actual event. For example, at the magnitude $m_b = 6.3$, 10 messages were sent.

Table IV-9a shows the number of messages sent. These are classified as a detected event, a redundant detection, or a completely false message. This was done for three test cases. The next table (Table IV-9b) normalizes this data to 50 events per day. We see that when a high false alarm rate (FAR) is used, the number of false messages increases while the other parameter effects seem to be insignificant.

The false alarm rate effect is analyzed in Figure IV-13 which shows: 1) the number of messages sent by the FAR (the curve labeled N) and 2) the percent of these classed as not good, as a function of the FAR (the curve labeled R). The curve labeled N is developed as the product of the two curves (R· N) and this is the expected number of good, either first or redundant, messages being sent at a FAR. A peak occurs in the $\overline{N}$ curve, at some FAR roughly estimated to be 0.57 false-alarms per hour.

This indicates that although more information enters the central facility at the high false-alarm rates, at a certain point the DAP makes more mistakes than at lower rates. Thus, the peak is a figure of merit for our baseline DAP alternative. A better DAP would clearly permit a higher FAR so that the quality of the detection association algorithm is a very significant factor in the overall system performance.

Since the communications system has been successfully tested for waveform requests rates to 50 per day (subsection IV-D), the 45 per day rate at the peak FAR means that the DAP is the performance limiting element in the system.

The above result is based on only four data points. Therefore, we associate a fair amount of uncertainty with the values derived. The curves of Figure IV-13 should be checked in later runs of the simulator.

TABLE IV-9a

DAP WAVEFORM REQUEST OUTPUT DATA

| Test Case | Test Conditions * | | | Number of WFR's Classed as Events | | | Total | Events |
|---|---|---|---|---|---|---|---|---|
| | $N\sigma$ | NA | FAR | Detected | Redundant | False | | |
| 1 | 5 | 4 | 0.5 | 79 | 44 | 56 | 179 | 200 |
| 2 | 4 | 4 | 0.5 | 42 | 43 | 56 | 171 | 177 |
| 3 | 5 | 4 | 2.0 | 32 | 17 | 41 | 90 | 89 |

* $N\sigma$ = Maximum standard deviations for association

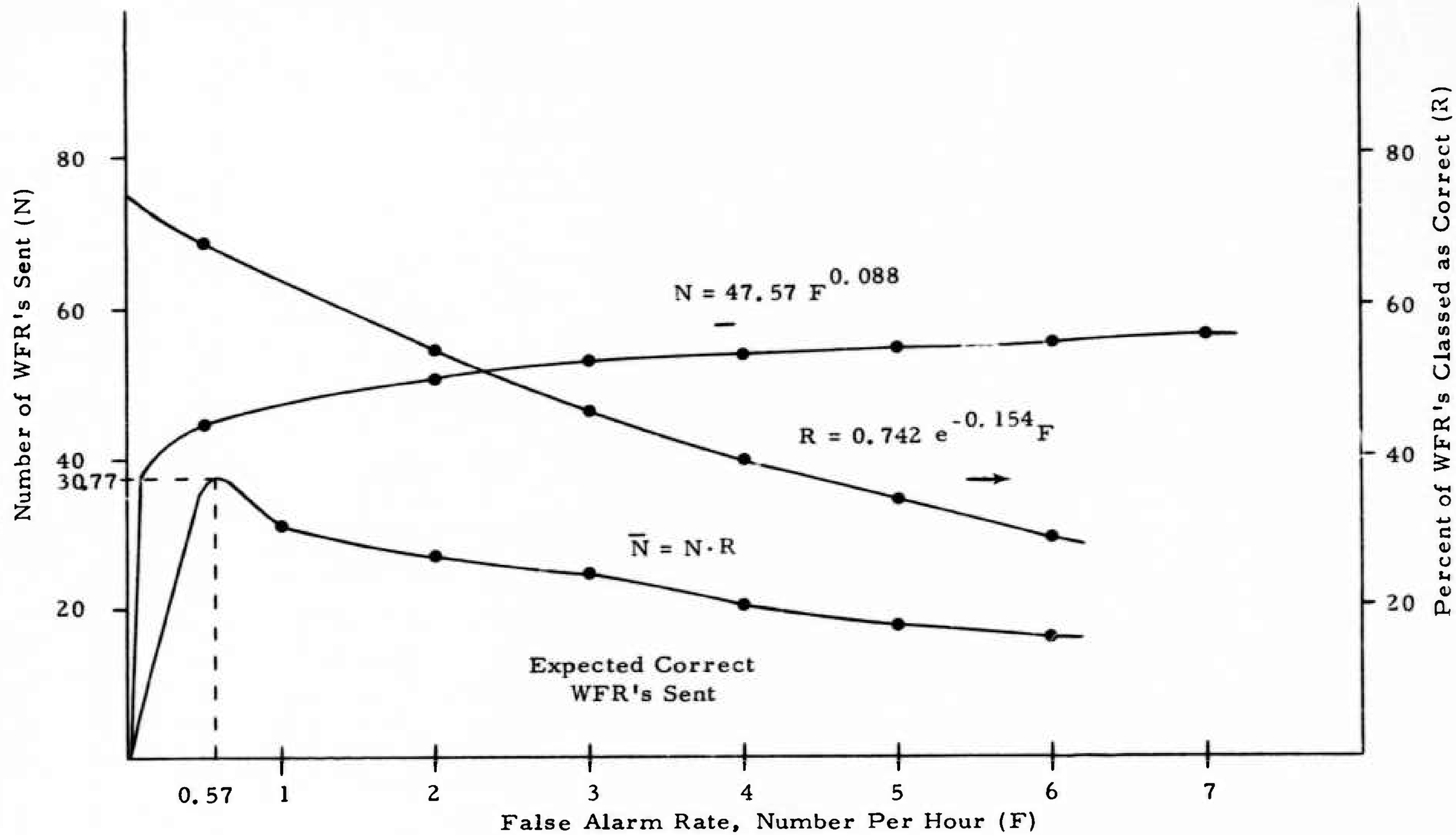
NA = Minimum number of bulletins for an event

FAR = False alarm rate for all stations.

TABLE IV-9b

DAP WAVEFORM REQUEST RATES
NORMALIZED TO 50 EVENTS PER DAY

| Test Case | Test Conditions | | | WFR's Per Day | | | Total | Days |
|---|---|---|---|---|---|---|---|---|
| | $N\sigma$ | NA | FAR | Detected | Redundant | False | | |
| 1 | 5 | 4 | 0.5 | 19.75 | 11.00 | 14.00 | 44.75 | 2.00 |
| 2 | 4 | 4 | 0.5 | 20.30 | 12.14 | 15.80 | 48.30 | 1.77 |
| 3 | 5 | 4 | 0.2 | 17.98 | 9.55 | 23.00 | 50.56 | 0.89 |




FICURE IV-13

EXPECTED NUMBER OF CORRECT WAVEFORM REQUEST MESSAGES SENT BY THE DAP AS A FUNCTION OF THE INFUT FALSE ALARM RATE

## F. NETWORK PERFORMANCE

The overall performance of the network is presented next, in terms of the usual measures, but primarily in terms of the network detection capability.

### 1. Reliability

From the diagram in subsection IV-D-1, and over the worst case path discussed in subsection IV-F-2, approximately 413 station failures can be expected for the network per year. These are before any failures caused by the network event classification processor. The primary effect on this processor is that several times a month a station that might have contributed to the classification problem either did not receive the signal or its data was lost due to communications failures. This may result in the need for an operator to attempt to recover this data on occasion. The net effect is that the operator would delay his processing. The effect on capability is not expected to be significant.

Other effects pertain to the system's management and maintenance, i.e., tracking the status of the failed stations, seeing to the logistics of maintaining the facility, and perhaps inserting the recovered data into the data base.

### 2. Delays

As documented in subsection IV-D, the cumulative delay for waveform messages to reach the central facility is 45 $\pm$ 20 minutes at 50 bps. This includes only 5 minutes for DAP operations and should be adjusted to allow at least 15 minutes processing. Therefore, the delay for a waveform to reach the central facility is estimated to be 50 $\pm$ 20 minutes.

Table IV-10 shows the estimated delay for various communications rates and processing sequences for an event. The total sequence is:

TABLE IV-10

CUMULATIVE PROCESSING DELAY TO ECP IN MINUTES (HOURS)

| Case | 50 BPS | 75 BPS | 2.4 KBPS | 4.8 KBPS |
|---|---|---|---|---|
| Single Beam Waveform | 50 $\pm$ 20<br>(0.83 $\pm$ 0.33) | 38 $\pm$ 10<br>(0.63 $\pm$ 0.17) | 15.7 $\pm$ 0.4 | 15.4 $\pm$ 0.23 |
| Above Plus Send One Failed Station | 85 $\pm$ 2.8<br>(1.4 $\pm$ 0.47) | 62 $\pm$ 14<br>(1.03 $\pm$ 0.23) | 16.4 $\pm$ 0.56 | 15.7 $\pm$ 0.32 |
| Above Plus All 19-SP Sensors | 750 $\pm$ 92<br>(12.5 $\pm$ 1.5) | 505 $\pm$ 47<br>(8.4 $\pm$ 0.78) | 30.3 $\pm$ 1.8 | 22.6 $\pm$ 1.04 |

1) stations receive the signal, all processing is completed by the DAP, waveform requests are sent to the field and the waveforms are received at the ECP, 2) the ECP analyst classifies the event by analyzing the beamed waveforms, and 3) for possible explosion events, the analyst requests all sensor data from 19 sensors. The last step involves considerable delay since the traces are sent one at a time and, to the communications system are equivalent to 19 waveforms. Therefore, the cumulative effect is that approximately 21 waveforms are sent through the communications system.

The table suggests that for all steps of this sequence, the delay could be as long as 15 hours (50 bps) before the last stage of ECP processing has begun. A requirement for 8 hours delay may still be met by the low-rate communications systems since, as we recall, the utilization of the facility varied from 10 to 80 percent indicating that improvement is possible if the communications are optimized.

3. Capability

The network detection capability for the four multi-region test cases is illustrated in Figures IV-14 through IV-17. The test conditions involved variations in: 1) the size of the error ellipse for the association ($N\sigma$), 2) the number of associates required before an event is declared by the DAP (NA), 3) the station false-alarm rate (FAR), and 4) the inclusion of three large arrays each having 87 short-period elements. The detection probabilities shown are the average over all of the seismic regions from which events were generated.

That the event frequencies are realistic can be seen from the histograms in these figures. We note that a relatively large number of events were processed by simulation, particularly in the 4.0 to 4.8 $m_b$ range. Of course fewer events were available at the higher magnitudes. Also, fewer events were processed in case 3 because the high false alarm rate slowed the simulation.

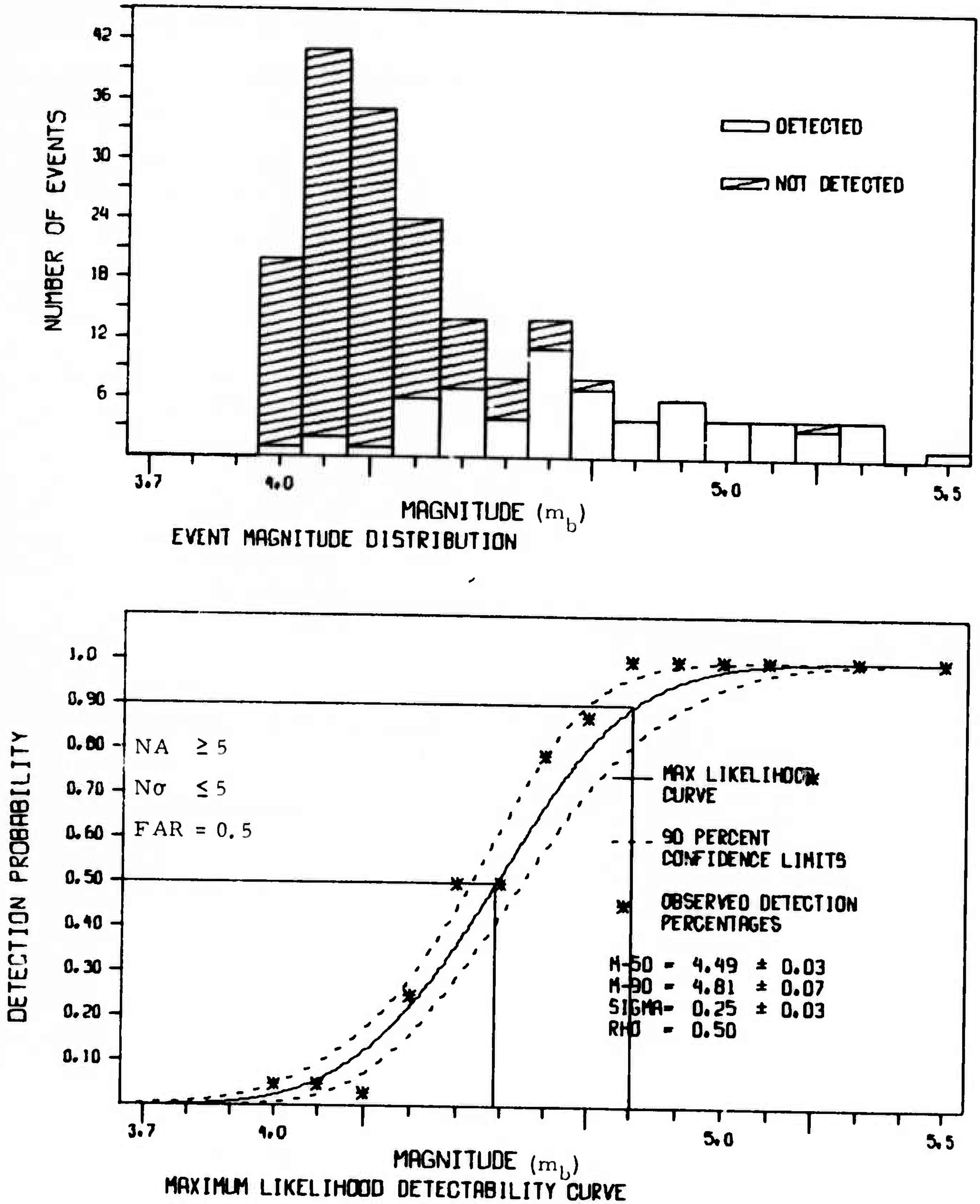
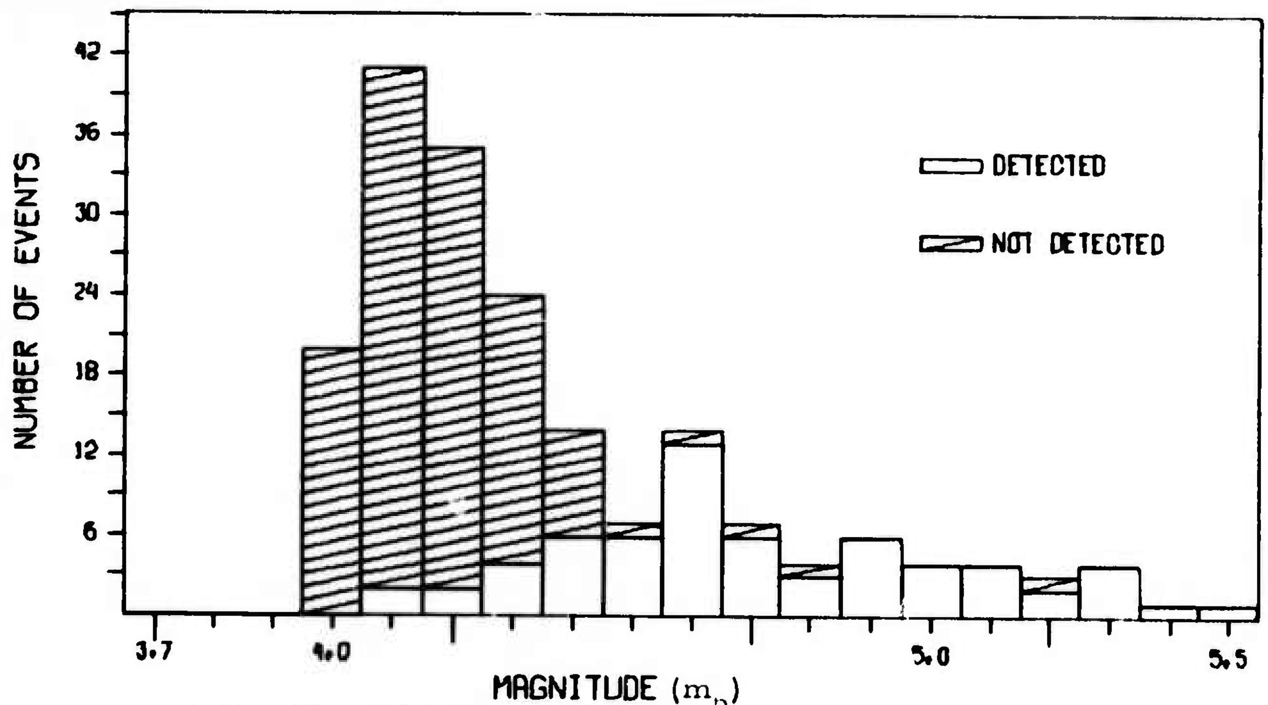
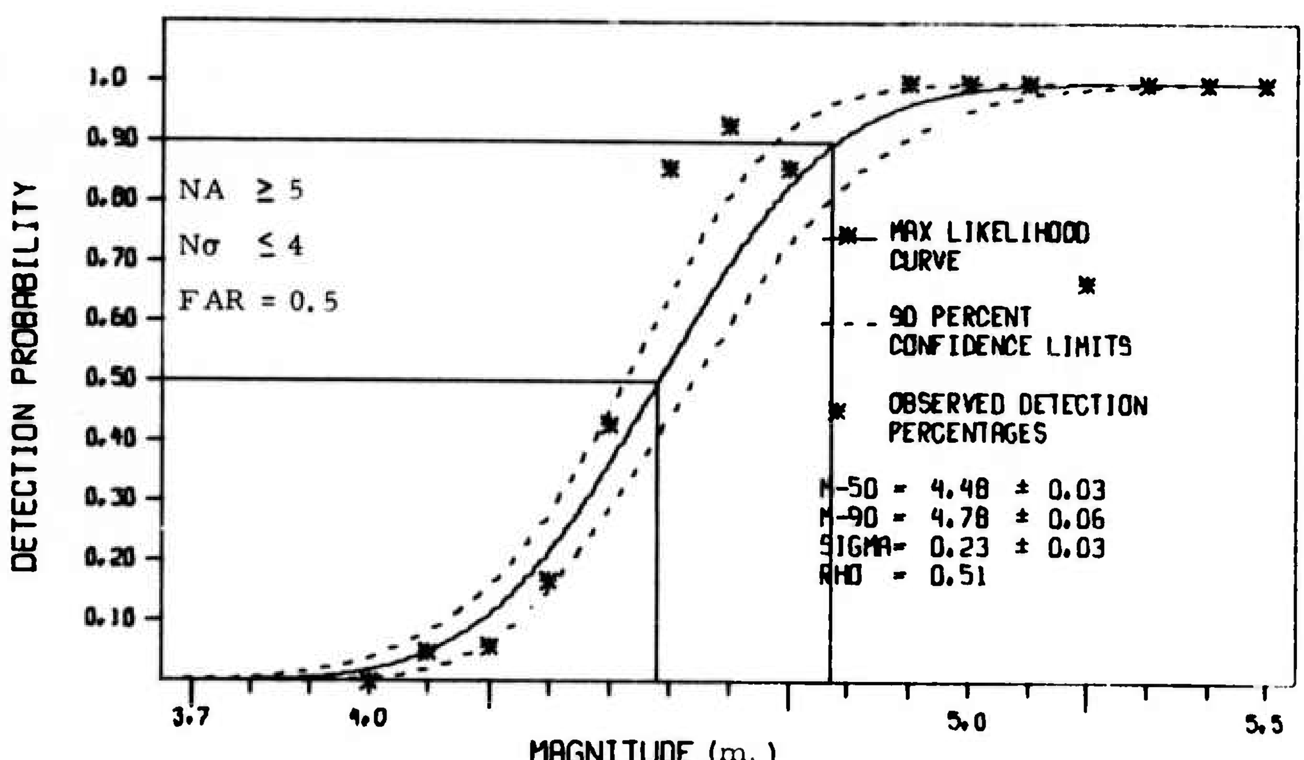



FIGURE IV-14

NETWORK DETECTION CAPABILITY FOR
0.5 FALSE ALARMS PER HOUR



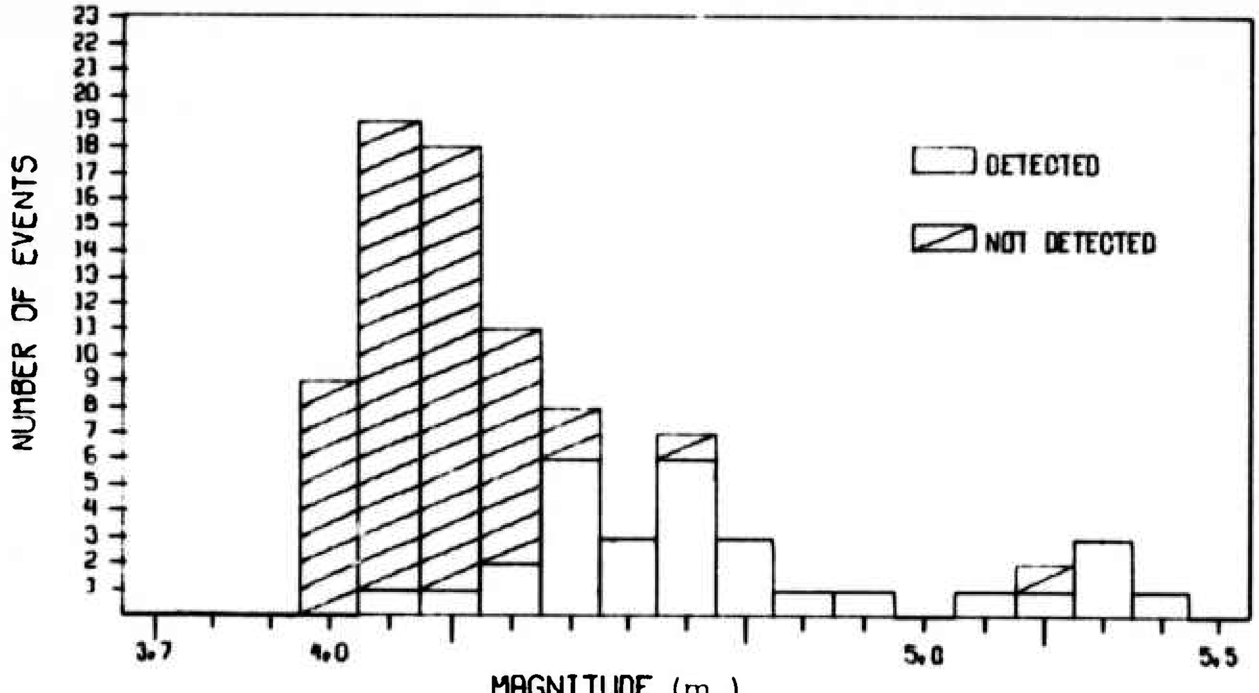

EVENT MAGNITUDE DISTRIBUTION



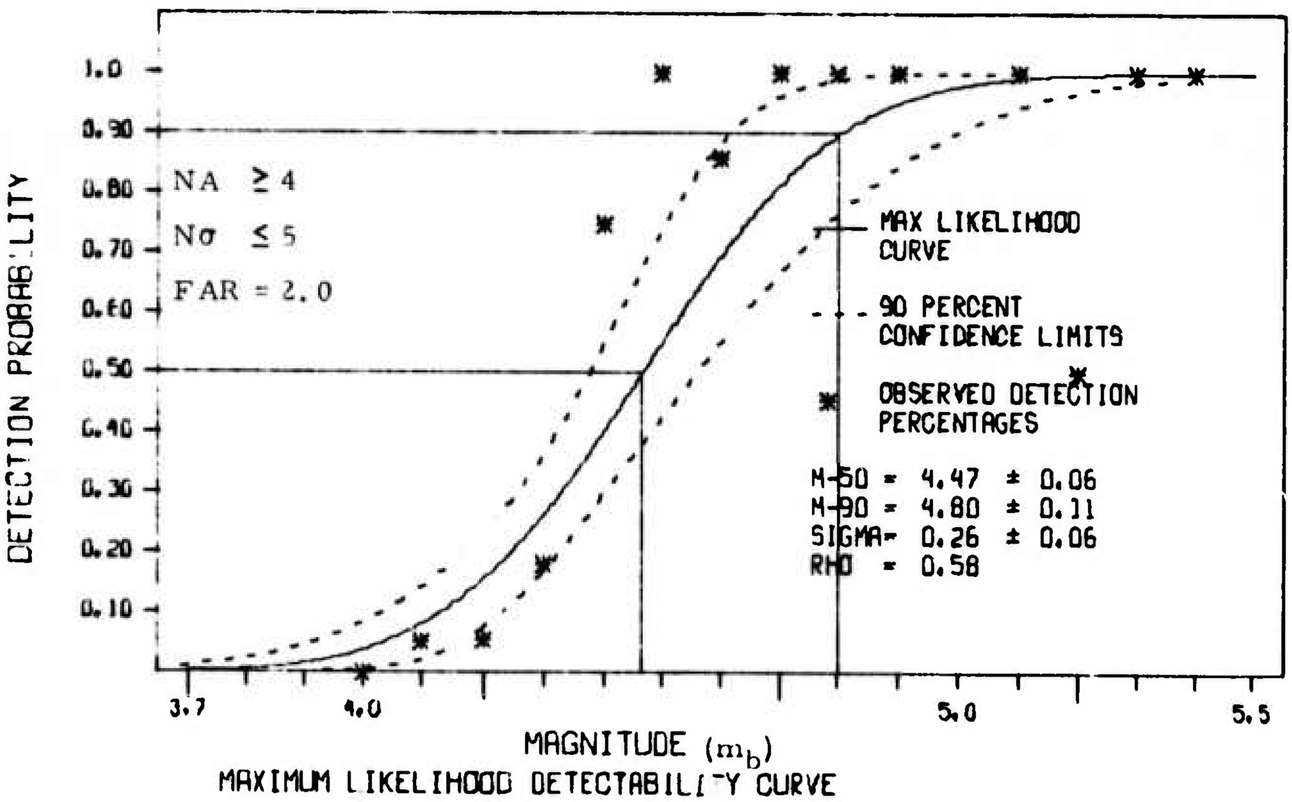

MAXIMUM LIKELIHOOD DETECTABILITY CURVE

FIGURE IV-15

NETWORK DETECTION CAPABILITY FOR SMALLER ERROR ELLIPSES



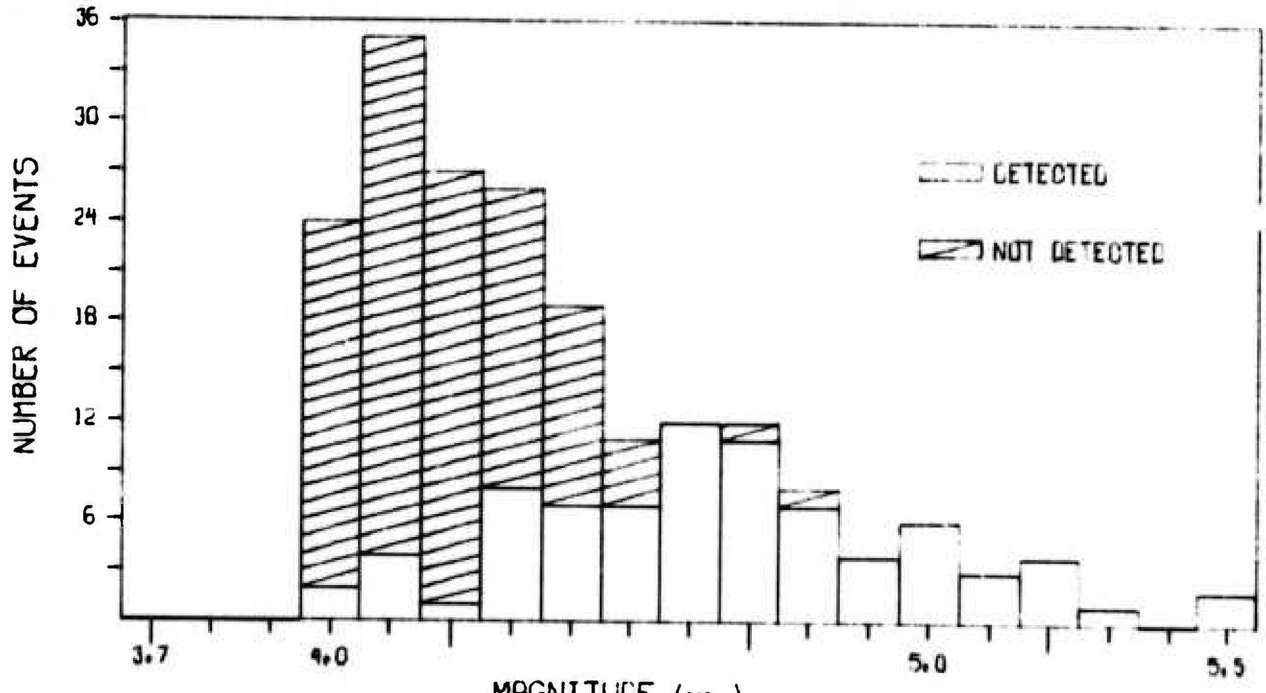
EVENT MAGNITUDE DISTRIBUTION



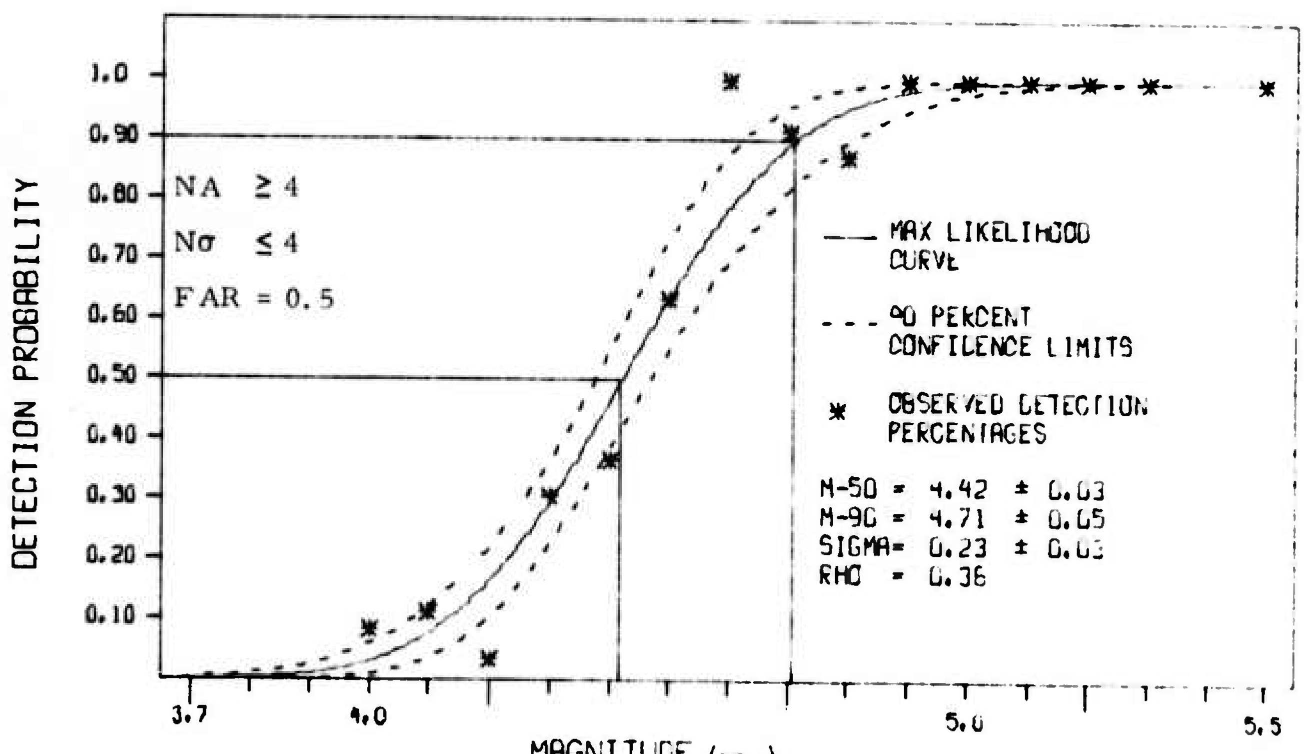
MAXIMUM LIKELIHOOD DETECTABILITY CURVE

FIGURE IV-16

NETWORK DETECTION CAPABILITY FOR A HIGH FALSE ALARM RATE




EVENT MAGNITUDE DISTRIBUTION




MAXIMUM LIKELIHOOD DETECTABILITY CURVE

FIGURE IV-17

NETWORK DETECTION CAPABILITY FOR THE NETWORK AUGMENTED BY THREE LARGE ARRAYS

Apparently the detection capability as shown in these figures and in Table IV-11 is somewhat below that estimated by the earlier analytic computer programs. The four station capability range for all cases at 0.9 detection probability is 4.7 to 4.9 $m_b$. The large array case improves the detectability by only 0.1 $m_b$ better than case 1 which is operated at the same parameter settings. Therefore, for these test conditions, the large arrays do not appear to be worth the approximately doubling of the network sensors. At the high FAR, case 3, the detectability also improved by at least 0.1 $m_b$. This result is not in conflict with the earlier result which included both correct and redundant detections.

Figure IV-18 shows the simulated and potential detection capability. The potential capability is developed from the station detection bulletin output as discussed in subsection IV-C. It assumes that the system from the communications facility through the central facility works perfectly. We see that for the base line system the loss is about 0.3 $m_b$ units.

In this subsection we presented simulation records, validation material, and results for the three facilities as well as for the network. The material is relevant to both the system design problem and the capability estimation problem. In addition, a number of areas for further investigation were noted which should be clarified. The next section summarizes the study results and conclusions and makes research recommendations.

TABLE IV-11

NETWORK DETECTION PROBABILITY DATA

| Test Case | Test Conditions | | | Magnitude, $m_b$ | | | | |
|---|---|---|---|---|---|---|---|---|
| | $N\sigma$ | NA | FAR | 4.3 | 4.4 | 4.5 | 4.6 | 4.7 |
| 1 | 5 | 4 | 0.5 | 0.250 | 0.500 | 0.500 | 0.785 | 0.875 |
| 2 | 4 | 4 | 0.5 | 0.167 | 0.428 | 0.875 | 0.982 | 0.857 |
| 3 | 5 | 4 | 2.0 | 0.182 | 0.750 | 1.000 | 0.875 | 0.928 |
| 4 | 5 | 4 | 0.5 | 0.308 | 0.368 | 0.636 | 1.000 | 0.916 |

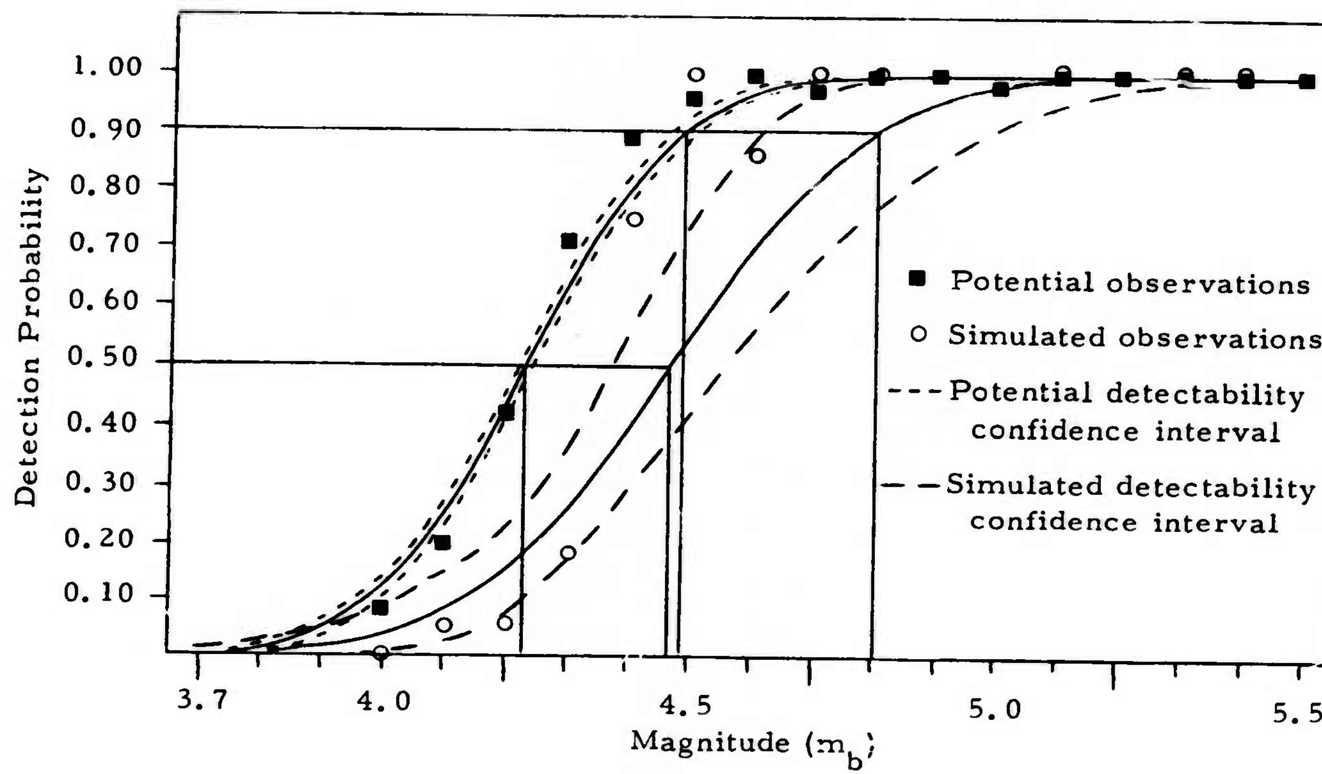



FIGURE IV-18

SIMULATED AND POTENTIAL NETWORK DETECTION CAPABILITY
(DATA TAKEN FROM FIGURES IV-6 AND IV-16)

## SECTION V

## CONCLUSIONS AND RECOMMENDATIONS

From the simulation results and their analysis presented in the last section, a number of conclusions and recommendations were indicated. These are summarized below beginning with the field stations.

### A. REMOTE FACILITY

Although remote facility detector alternatives were not simulated, it was apparent that two factors to consider in selecting between candidate detectors are:

- Significant differences in the low threshold area of the detector operating characteristic
- The impact on the processing time of poor detectors due to increased back communications.

The first point seems obvious except that one is rot used to comparing operating characteristics in the extemes. But this area is most important for successful operation of the network processing. The second factor is difficult to evaluate since the station processor design is involved. That is, are waveform requests serviced in background area of the computer or do they interrupt the detection processing or do they begin processing when the detector is finished? In the last case a poor detector, even if it allows more time for such requests, may fall behind because of more erroneous waveform requests. If these factors are taken to account, it is possible to select detector alternatives for the network without simulation. Also, the simulator provided gross statistical models that can be used in such evaluations.

## B. COMMUNICATIONS

The analyses and measurements from the simulation led to the following conclusions regarding the communications system:

- A full-duplex (simultaneous two-way transmission) system offers only marginal improvement in the line utilization.
- The performance of the communications system is sensitive to the management of the facility.
- Communications processors should interface with the processing facilities by disk rather than by allowing direct access.
- The remote processor should buffer at least one waveform message and use fixed buffer allocation to improve utilization and to simplify the software.
- Multiple access methods at the central facility affect the communications utilization.
- The worst case delay for a low-rate system (50-75 bps) is 10 to 15 hours without optimization.

The improvement offered by the full-duplex system was shown in Figure IV-8 to be about 0.8 percent, whereas the utilization due to varying loads ranges from 10 to 80 percent. So rather than pay, say twice as much for the full-duplex system, better management of the half-duplex system is indicated. If greater capacity is needed, however, then wideband half-duplex will maximize the useful capacity.

The communications processors were seen to have time-varying queues so that some buffering by a disk unit is necessary as the queue lengths extended beyond that which could be buffered in a reasonable core memory. In the case of a failure more buffering is needed beyond that indicated by simulation. At the remote facility at least four waveform messages can be expected and at the central facility at least 20 waveform request messages needed to be buffered. To maintain the system utilization with the simplest possible software at least one waveform message should be in the RCP memory. The RCP buffered internally by packets seems to save only memory at the cost of more elaborate software. Similarly, fixed rather than dynamic buffer allocation will simplify the software.

## C. CENTRAL FACILITY

Subsection IV-E presents the central facility results which are summarized below:

- The number of data path failures per year at the central facility is expected to be 138 before the detection association processor (DAP) and 275 before the event classification processor (ECP), depending on the processing sequence
- No significant queues or delays were noted at the central facility
- The DAP utilization was around 7 percent
- The baseline DAP algorithm used in this study is limited by incorrect associations at a false-alarm rate of 0.57 alarms per hour.

Reliability, while not expected to impact the system performance, may cause management difficulties. Lack of significant queues or delays is due to the under utilization of the DAP. In the event of a failure queues will develop, but the given central facility configuration can recover easily. Since the DAP is limited in the useful FAR, the output waveform request rate is below the present capacity of the communications system.

## D. TOTAL SYSTEM

At the total system level, the following summary conclusions are reached:

- The number of data path failures may reach 400 or so annually. This may present a major problem to the system's management but is not expected to impact the network capability
- The major time delay in the network is due to the time to send waveform messages to the central facility
- The major queue in the network is at the remote facility for outgoing waveform messages
- The four station network detection capability is in the 4.7 to 4.9 range for 90 percent detection probability when averaged over all regions. This is about 0.3 $m_b$ units worse than the theoretical potential of the network
- The major limitation on the network performance is in the DAP. A better DAP than the one simulated here would allow a significantly improved network detection capability.

## E. RECOMMENDED RESEARCH

Rather than arriving at system specifications, at this time the base-line simulation has indicated the need for further research to improve the design. Network detection processing appeared to be the limiting factor in the simulation. Therefore, further development of this subsystem is recommended. The development should focus on the suppression of unwanted waveform messages in addition to the improvement of the processor operating characteristics. Interactive processing may be useful at this point. Also, extension of the association criteria to include magnitude, depth, and ellipse rotation should be considered.

Once the network processing limitation is removed, the next limitation is in the quantity of data that can be delivered by the communications system. The most promising area here is in the operating procedures of 1) when to request data, 2) what to request, and 3) which stations to select. Clarification in this area will allow maximum utilization of the communications. Other optimizations of the communications system are possible such as the best multiple access method, data compression, coding, and the like. However, these factors are considered less important in improving overall system performance.

Systems management was for convenience, omitted from the simulation. The problems involved are not simple, and the effect on the on-line system of poor maintenance, over or under staffing, and lack of supplies and loss of other control functions could be significant to the system performance. Therefore, some effort to obtain information for management control should be an integral part of the system.

The simulator may be used to develop fast 'test-beds' for the other research efforts. Therefore, it is recommended that the simulator be extended and updated along with the system.

To summarize these recommendations, the areas for further research as identified by the simulator are:

- Development of network detection processing methods

- Optimization of the communications procedures, especially the data request procedure
- Study of the system management problems and requirements
- Development of fast test-bed simulators.

Finally, it is recommended that the simulator be updated as the system evolves (as a guide in this development and for the other application objectives identified in Section III).

## SECTION VI

## REFERENCES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# APPENDIX A

This section is intended to provide general flow charts for the simulator main program and facility subprograms, Figure A-1 is the main program flow chart. It shows that the simulator can be broken into the three facility subprograms REMOTE, COMNET and CENTER Tape inputs or macro-models may be substituted for the detailed programs simply by interfacing with the subprogram arguments which are the facility input/output time series.

Figure A-2 is a flow chart of the communications facility simulator (COMNET). Similar to the above approach, the program can be divided into the network elements if this is desired or other element models or prototypes can be substituted into the program.

Figure A-3 is of the Central facility (CENTER). Similar divisions and substitutions can be made.

It is anticipated that later program documentation will follow this report when it is finalized.

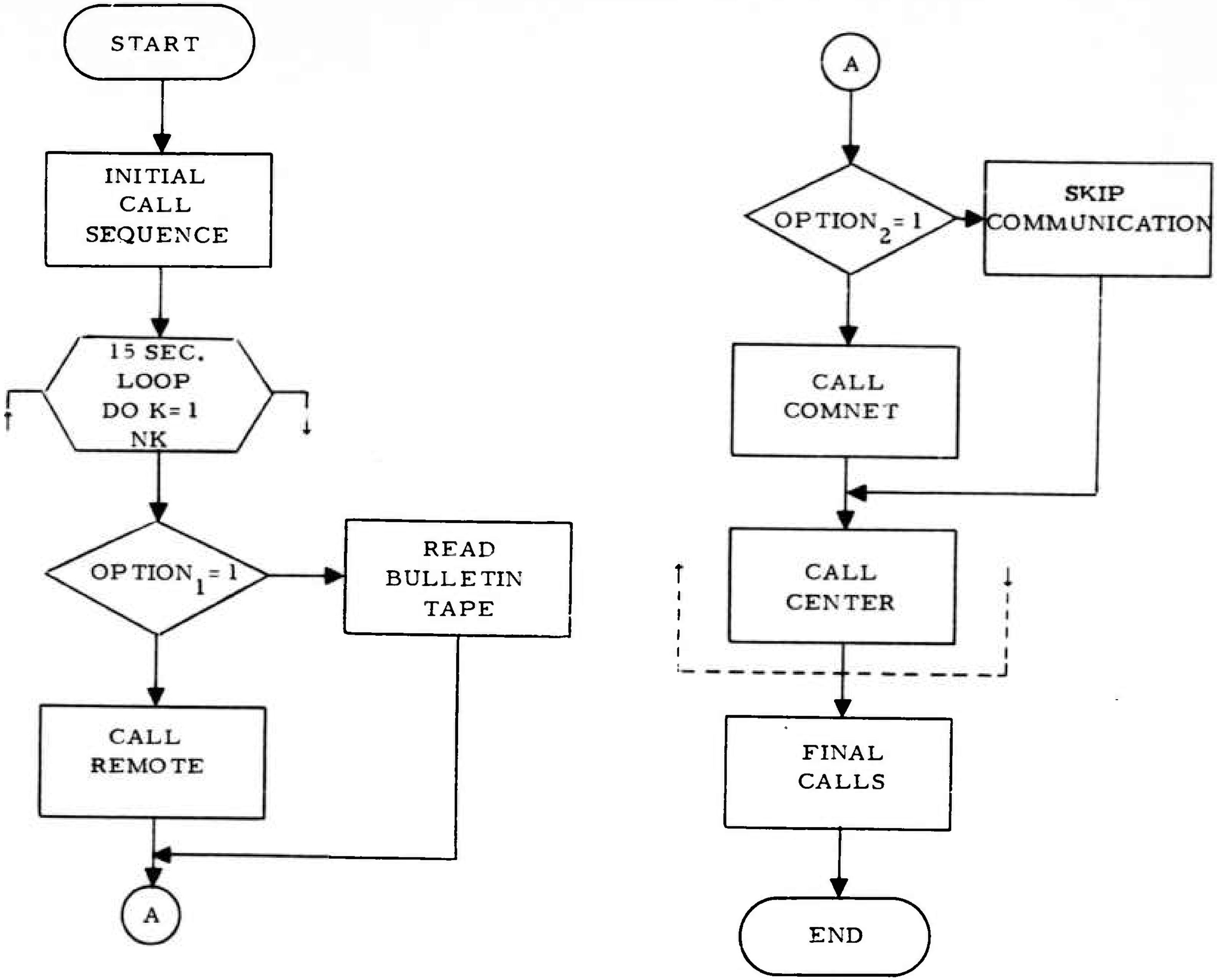


FIGURE A-1

SEISNET MAIN PROGRAM

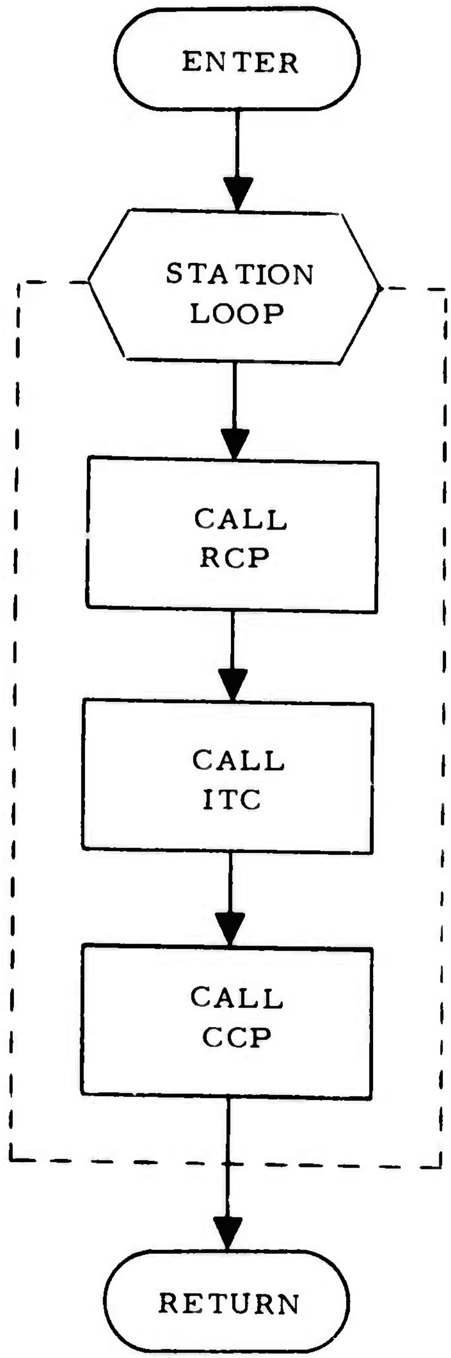


FIGURE A-2

SUBROUTINE COMNET

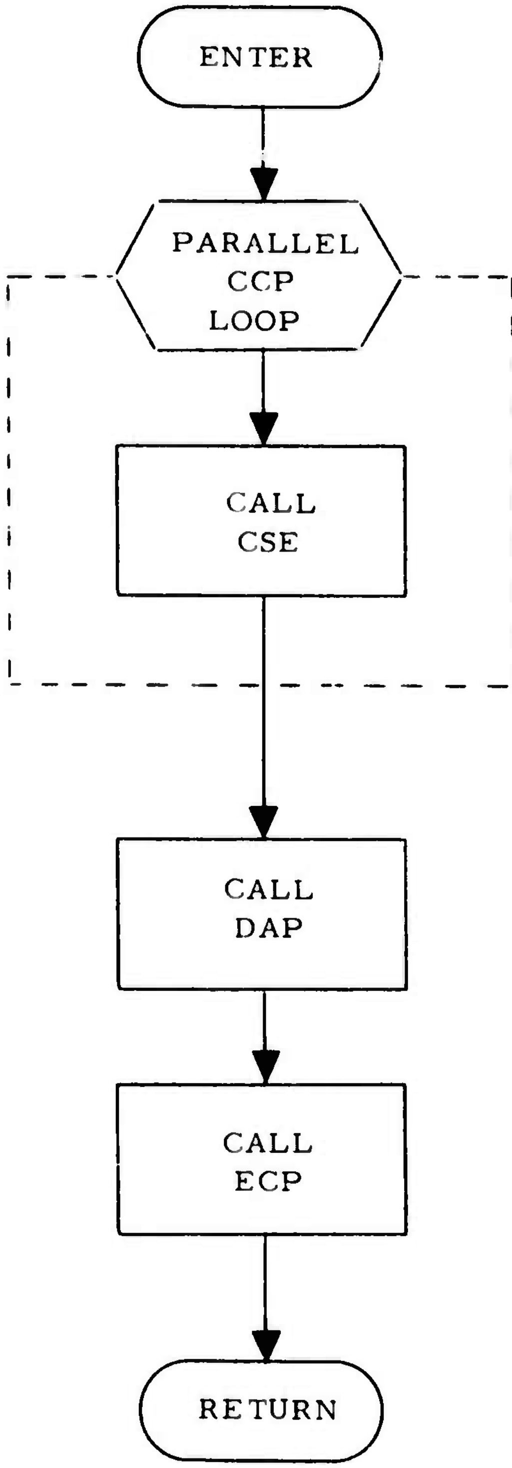


FIGURE A-3

SUBROUTINE CENTER